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A rock-plant filter bench-scale study and computer model

Skipper, Donna Gail, Ph.D.

The Louisiana State University and Agricultural and Mechanical Col., 1990

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A ROCK-PLANT FILTER BENCH-SCALE STUDY AND COMPUTER MODEL

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Civil Engineering

by
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B.S., University of Alabama, 1975
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December, 1990

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ABSTRACT

In Part One, three bench-scale rock filters containing 2 feet of gravel were investigated. Two of the filters were planted with Sagittaria lancifolia and Scirpus validus, while the third filter was an unvegetated control filter. During a preliminary portion of this study, the BOD_5 surface loading was held constant at 4.96 g/day/m^2. The BOD_5 mass removal percentages at this time averaged 75%, 60%, and 44% for the Scirpus, Sagittaria, and control systems, respectively. Following this constant loading rate, an 80-day experiment was run on the filters using eight combinations of two flow rates and four influent BOD_5 concentrations, each combination remaining constant for ten days. These combinations resulted in BOD_5 surface loadings from 4.63 to 30.96 g/day/m^2. Overall average BOD_5 removal percentages during this latter portion of the study were 69%, 57%, and 47% for the Scirpus, Sagittaria, and control systems, respectively. ORP and DO measurements within these systems indicated no free oxygen available at any depth. TKN removal was higher in the plant systems relative to the control, with the Scirpus system achieving a higher overall removal than the Sagittaria system. This increased nitrogen removal may be due to nitrification occurring in the thin aerobic zone surrounding portions of the plant roots.

The data gathered from the Part One bench-scale study

was used in Part Two to develop a computer model for predicting effluent BOD_5 concentrations. This computer model was then applied to a full-scale municipal system. As determined by the sum of squared residuals parameter, consistently more accurate predictions were obtained with the computer model than with two currently used equations for all three bench-scale systems and the full-scale system. An analysis of the computer model BOD_5 mass balance suggests that microbial degradation occurring on the rock surfaces is responsible for the greatest decrease in BOD_5; furthermore, this degradation rate increases in the presence of aquatic plants. By making several simplifying assumptions, the computer model is reduced to a manageable equation using easily obtained parameters.

PART ONE:
THE BENCH-SCALE STUDY

Chapter 1
INTRODUCTION

In the last few decades, population growth and increasingly stringent environmental regulations have inspired new wastewater treatment methods, as well as revisions to existing methods. One of these attractive wastewater treatment alternatives is aquatic plants growing in a rock filter, or a rock-plant filter. Due to low operation and maintenance costs, rock-plant filter systems are increasing in popularity, especially in the southeastern United States; yet, no proven design criteria have been established. Although aquatic plants in wastewater treatment have been studied in Europe and the United States over the past 20 years, much of this research has centered on floating plants, such as water hyacinths and duckweed. These plants are advantageous in upgrading treatment ponds; however, clogging of waterways, die-off in cool climates, and the production of anaerobic conditions have posed problems in many installations. By contrast, rock-plant filters employ emergent aquatic plants which are more resistant to cool climates and do not usually clog waterways. To better determine optimal designs for rock-plant filters and to develop a research tool for predicting responses of this type of system to climate and organic loadings, data from this bench-scale study will be used in Part Two to derive a computer model for predicting effluent five-day biochemical oxygen demand (BOD_5) concentrations.

Chapter 2
RELATED RESEARCH

Since the 1970's, research on rock-plant filters has been conducted using various types of aquatic plants, retention times, and wastewater sources. Organic and nutrient removal rates observed have been varied and sometimes inconsistent, however, as discussed below.

In one of the earlier studies, Spangler, et al. (1976) planted bulrush (Scirpus validus) in flow-through trenches which were PVC lined and gravel filled to study the effect of retention time, nature of wastewater applied (primary or secondary treatment effluent), and frequency of harvesting on effluent quality. The retention times they used (5 hours, 16 hours, and 10 days) yielded equivalent BOD_5 reductions for both control and bulrush basins. It was noted, however, that flow regulation was poor in the control basin and higher loadings were actually applied to the bulrush basins as compared to the control. For primary effluent, BOD_5 reduction was nearly 10% greater when compared to secondary effluent. Furthermore, harvesting resulted in no observed changes in effluent quality.

Contrary to Spangler, et al.'s observations, a study by Wolverton (1982) indicated a significant difference in BOD_5 removal between an unvegetated filter and a filter containing reed (Phragmites communis). BOD_5 removal percentages for the control filter were 62% and 83% after 6 and 24 hours retention time, respectively; the rock-reed filters achieved 87% and 96% BOD_5 removal for the same retention times. TSS removal after 24 hours retention was 44% for the control filter and 83% for the rock-reed filter. In addition, nutrient removals were an order of magnitude higher in Wolverton's rock-reed filter relative to his control.

Relatively equal levels of BOD_5 removals in vegetated and unvegetated filters were, however, observed by Wolverton, et al. (1983) in a later study. This batch experiment began by first settling raw sewage anaerobically for 24 hours, then delivering the effluent to various rock filters each containing a different aquatic emergent plant plus an unvegetated control. Plants used include reeds (Phragmites communis), cattails (Typha latifolia), rush (Juncus effusus), and bamboo (Bambusa multiplex). The filter influent BOD_5 was adjusted to approximately 60 mg/l and 300 mg/l on separate occasions by adding different amounts of water hyacinth juice to the raw sewage. The results of this study indicated retention times of 6 and 29 hours were required to achieve the 30 mg/l BOD_5 secondary treatment standard for the 60 mg/l and 300 mg/l influent BOD_5 loading, respectively. Although the BOD_5 removal in the vegetated filters was comparable to the control, the system containing reeds performed slightly better than the other systems.

The fate of nitrogen in secondary treatment effluent subjected to bulrush, cattail, and reed filter systems was studied by Gersburg, et al. (1983, 1984). They found denitrification to be responsible for the majority of the nitrogen losses within the aquatic filters. Enhancement of the denitrification process was effected by adding a carbon source to elevate the carbon: nitrate ratio to 1.7, the ratio found to be optimal for denitrification. Without a carbon supplement, nitrogen removal was only about 25% in vegetated and unvegetated beds; however, with the addition of methanol, nitrogen removal increased to approximately 95% in the vegetated beds. Retention time within the beds was about 3 days for this study.

In a later study, Gersberg, et al. (1986) treated primary wastewater in four 2.5 feet deep gravel ditches containing bulrush (_Scirpus validus_), reed (_Phragmites communis_), and cattail (_Typha latifolia_), plus an unvegetated control. Parameters monitored during this study included ammonia, BOD_5, and TSS. Ammonia removals were found to be 94%, 78%, and 28% for bulrush, reed, and cattail, respectively. BOD_5 removals for bulrush, reed, cattail, and the control were 96%, 81%, 74%, and 69%, respectively. Essentially equal TSS removal was observed in all ditches and was, therefore, assumed to be an exclusively physical process. In addition, depth of root zones were recorded for each species. Cattail was found to have the shallowest root zone of approximately 12". The bulrush root zone extended to a depth of over 24"; while the root zone of reed averaged around 30".

Chapter 3
METHODS AND PROCEDURES

Three 5 foot long by 1.5 feet wide, rectangular, welded-aluminum tanks, as shown in Figure 1.1, housed the filter systems. Each tank had an interior urethane coating and was constructed as shown in Figure 1.2. The influent flow entered near the bottom of one end of each tank through a perforated PVC pipe spanning the width of the tank while the effluent spilled into a standpipe at the opposite end of the tank. Oxidation/ reduction potential (ORP) probes were placed near the mid-tank access ports at mid-depth. These tanks were installed in a greenhouse which supplied an equal amount of sunlight to all tanks. The water temperature of all three tanks remained within 1°C of each other and varied from 21°C to 31°C during this study.

On November 19, 1988, one tank was planted with ten Sagittaria lancifolia (duck potato) seedlings and another tank with ten Scirpus validus (bulrush) seedlings. These plants grew for 5 months prior to beginning analyses. During this 5 months, a solution containing Hydrosol (a hydroponic fertilizer by Peters), CaNO3, and dextrose was recirculated through each tank at a flow of 500 to 1000 ml/min. This solution was replenished twice per week with daily dextrose additions. On January 25 and then again on March 8, 1989, the tanks were seeded with activated sludge mixed liquor.

Figure 1.1: Photograph of Bench-Scale Rock-Plant Filter Systems

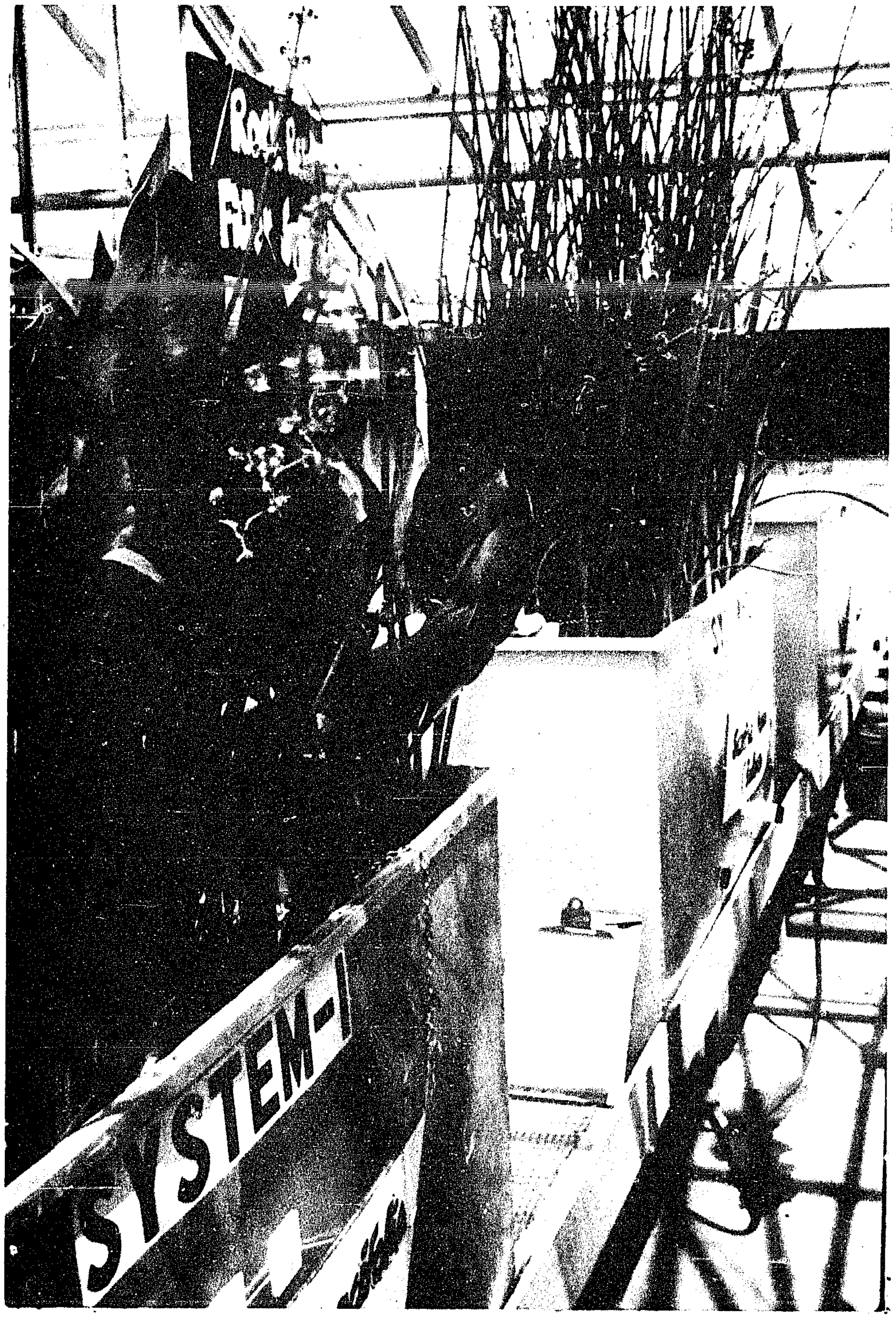
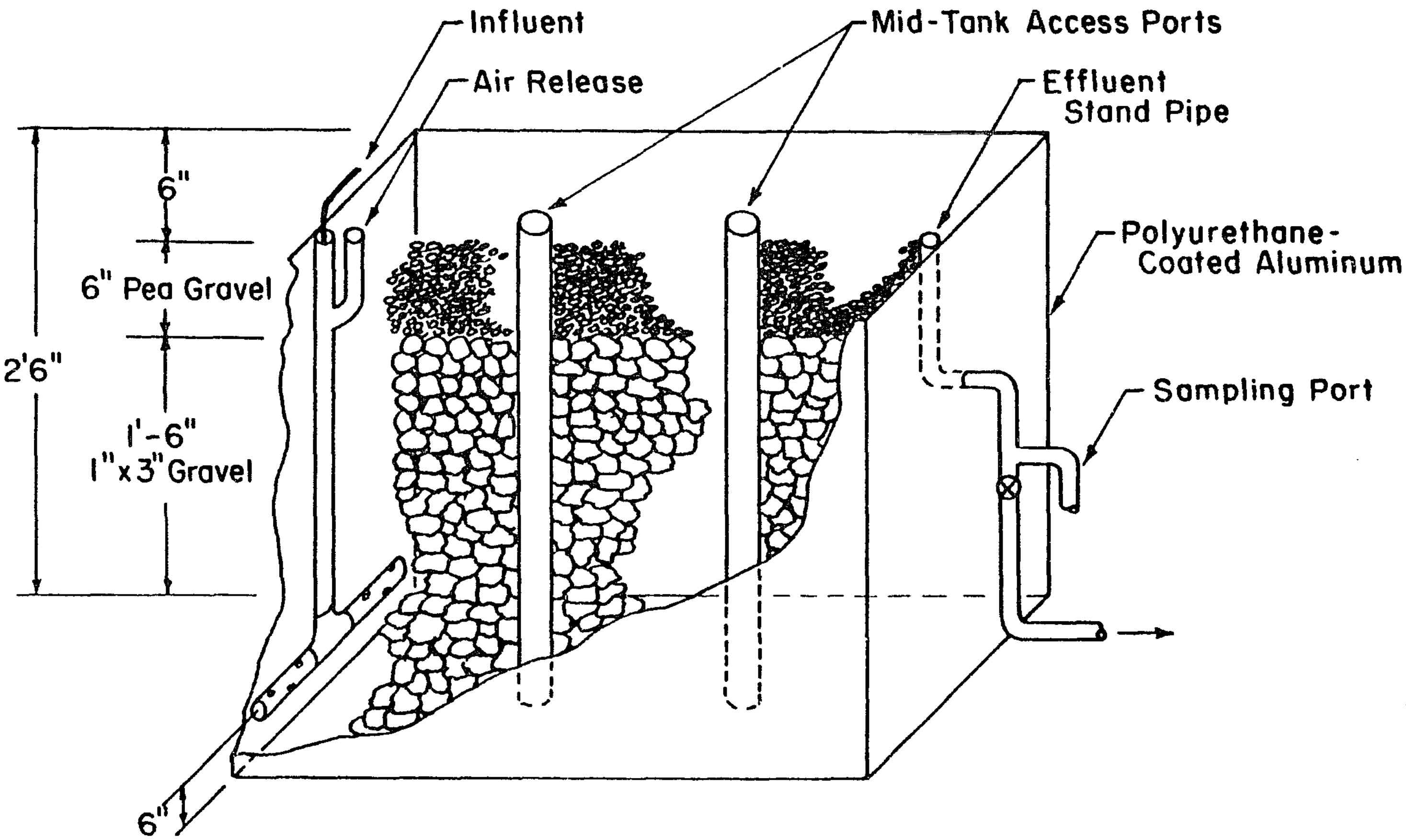


Figure 1.2: Bench-Scale Rock-Plant Filter Systems Inner Tank Details

(Not to Scale)



Section 3.1: Preliminary Investigation

After the 5 month start-up period, the flow through the tanks was changed to once-through flow using a synthetic wastewater containing constituents listed in Table 1.1. Although using a synthetic wastewater creates a somewhat unrealistic situation, it allows the effluent to vary while the influent is controlled. The wastewater recipe shown in Table 1.1 is a result of several trial mixtures. Initial mixtures contained glucose and ammonium sulfate as carbon and nitrogen sources, respectively. This was changed when most of the BOD_5 was consumed in the reservoir before entering the filters. Nutrient broth corrected this situation satisfactorily; however, the nitrogen source in nutrient broth is solely organic, which is found in primary wastewater but not usually in secondary wastewater where ammonia is the typical nitrogen form. To feed each filter with synthetic wastewater, separate chemical feed pumps (Cole Parmer Model N-07141-28) distributed wastewater from a common reservoir to each filter. This wastewater was mixed fresh daily.

Initially, the goal was to arrive at a steady percentage of organic removal before stepping to a different hydraulic/ organic loading scheme. No steady removal rate was found, however, after over a month at a flow of 80 ml/min and an organic loading of 4.96 g BOD_5/day/m^2 surface area (30 mg/l BOD_5 influent).

TABLE 1.1: SYNTHETIC WASTEWATER RECIPE

CONSTITUENT	CONCENTRATION (mg/l)
$MgSO_4.7H_2O$	300
$FeCl_3.6H_2O$	14
$MnSO_4.H_2O$	5
K_2HPO_4	120
KH_2PO_4	30
$CaCO_3$	14
Difco Nutrient Broth	77, 153, 227, and 304

Although BOD_5 mass removal was the major focus of this study, many of the organic removal measurements were calculated through chemical oxygen demand (COD) values due to the greater ease, speed, and accuracy of the COD analysis in comparison with the BOD_5 analysis. Ordinarily this relationship is not reliably consistent; however, with a controlled wastewater, such as the one used in this study, the ratio of these parameters should be relatively constant. Measurements of both were performed here to verify this relationship.

Analyses performed on each system effluent and a composite of the system influent (half fresh and half 24 hours old) during this preliminary portion of the study, included daily pH measurements; COD three times per week; and BOD_5, total Kjeldahl nitrogen (TKN), ammonia, and nitrate once per week. Each of these analyses were performed in triplicate. In addition, daily measurements of the air and water temperature, influent and effluent flow rates for each tank, and ORP at two points within each tank were obtained. Measurements of pH were taken at each of the four sample points with an Orion pH meter. COD measurements were facilitated through the use of standard range COD twist-tubes supplied by O.I. Corporation. For BOD_5, total Kjeldahl nitrogen (TKN), ammonia, and nitrate, methods specified in the 16th edition of Standard Methods for the Examination of Water and Wastewater (APHA, 1975) were employed. Flow rates were obtained manually by measuring the volume accumulated in one minute. Platinum probes installed at two points in each tank yielded ORP measurements. Data on plant growth and nitrogen content were recorded by randomly selecting 6 or 12 plants from each tank and drying them at 70°C to a constant weight. By counting the number of plants in each tank at the time of sampling, the above-grade dry weight of plant matter for each system was estimated. A small portion of dried plant matter from each tank was ground in a Wiley mill equipped with a #40 sieve for TKN analysis to obtain a plant TKN mass estimate for each tank. Raw analytical data from these preliminary analyses are listed in Appendix A.

Section 3.2: Eighty-Day Variable Loading Investigation

When steady-state operation was not obtained in a feasible time-frame, an alternative monitoring program was contrived. This program involved randomly changing the influent BOD_5 concentration in consecutive ten-day periods at two flow rates. The four influent BOD_5 concentrations (28, 78, 107, and 51 mg/l) were first applied under a flow of 80 ml/min (42 hour theoretical retention time), which resulted in BOD_5 surface loadings of 4.63, 12.90, 17.69, and 8.43 g/day/m^2. The influent concentrations listed above were then repeated under a 140 ml/min flow (24 hour theoretical retention time), giving BOD_5 surface loadings of 8.10, 22.57, 30.96, and 14.76 g/day/m^2. During each ten-day period, the effluent from each filter and an influent composite were analyzed on days 4, 8, 9, and 10 for BOD_5, TKN, and ammonia; and on days 2, 4, 6, 8, 9, and 10 for COD. Only random nitrate analyses were performed since negligible amounts of this compound were measured during the preliminary portion of this study. Daily measurements of water temperature, pH, and ORP in each tank were also obtained. The influent pH was adjusted daily to between 7.0 and 7.5 by addition of sulfuric acid. Ambient air temperature and influent and effluent flow measurements were also recorded daily. Above-grade dry plant matter weight and TKN plant mass were analyzed at the end of every 10 day period for each vegetated filter. Raw analytical data from this 80-day variable loading study is listed in Appendix A.

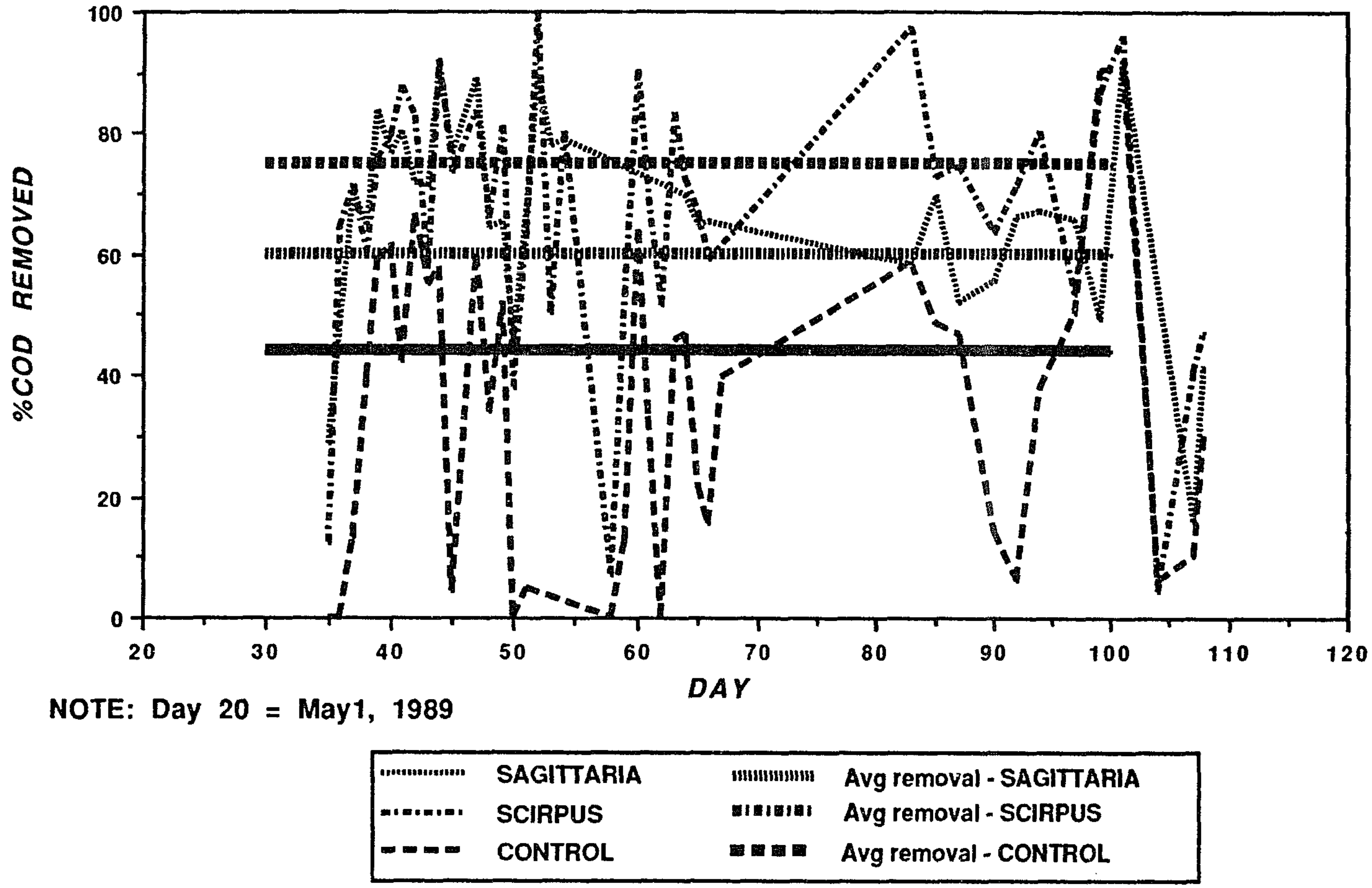
Chapter 4
RESULTS

Section 4.1: Preliminary Investigation

During the preliminary period of this study, oscillation of the COD data at a constant influent BOD_5 of approximately 30 mg/l and a flow of 80 ml/min, even after a month, indicated that a steady-state situation had not been achieved. To verify this statistically, the 95% confidence interval about the mean for each filter was calculated separately using individual triplicate COD analyses from the last five samples analyzed. Values lying to each side of this confidence interval in all three cases suggested a steady-state had not been reached in any of the three filters. An analysis of variance conducted on this data, however, indicated a very significant difference in COD removal between filter systems, below the 0.5% confidence level. Overall average COD removal percentages (by mass) were 75%, 60%, and 44% for the *Scirpus*, *Sagittaria*, and control systems, respectively.

As shown in Figure 1.3, the *Scirpus* performed slightly better in COD removal than the *Sagittaria* system, with the control lagging behind 10 to 40 percent. The high variability noted in Figure 1.3, particularly for the control, is due partly to poorly controlled flowrates and no pH control. In addition, from Day 56 to Day 102, the control system was operated with a rotary feed pump after the original pump shut off on Day 54. Ranking of the

FIGURE 1.3 - MASS %COD REMOVED VS TIME DURING PRELIMINARY EXPERIMENT



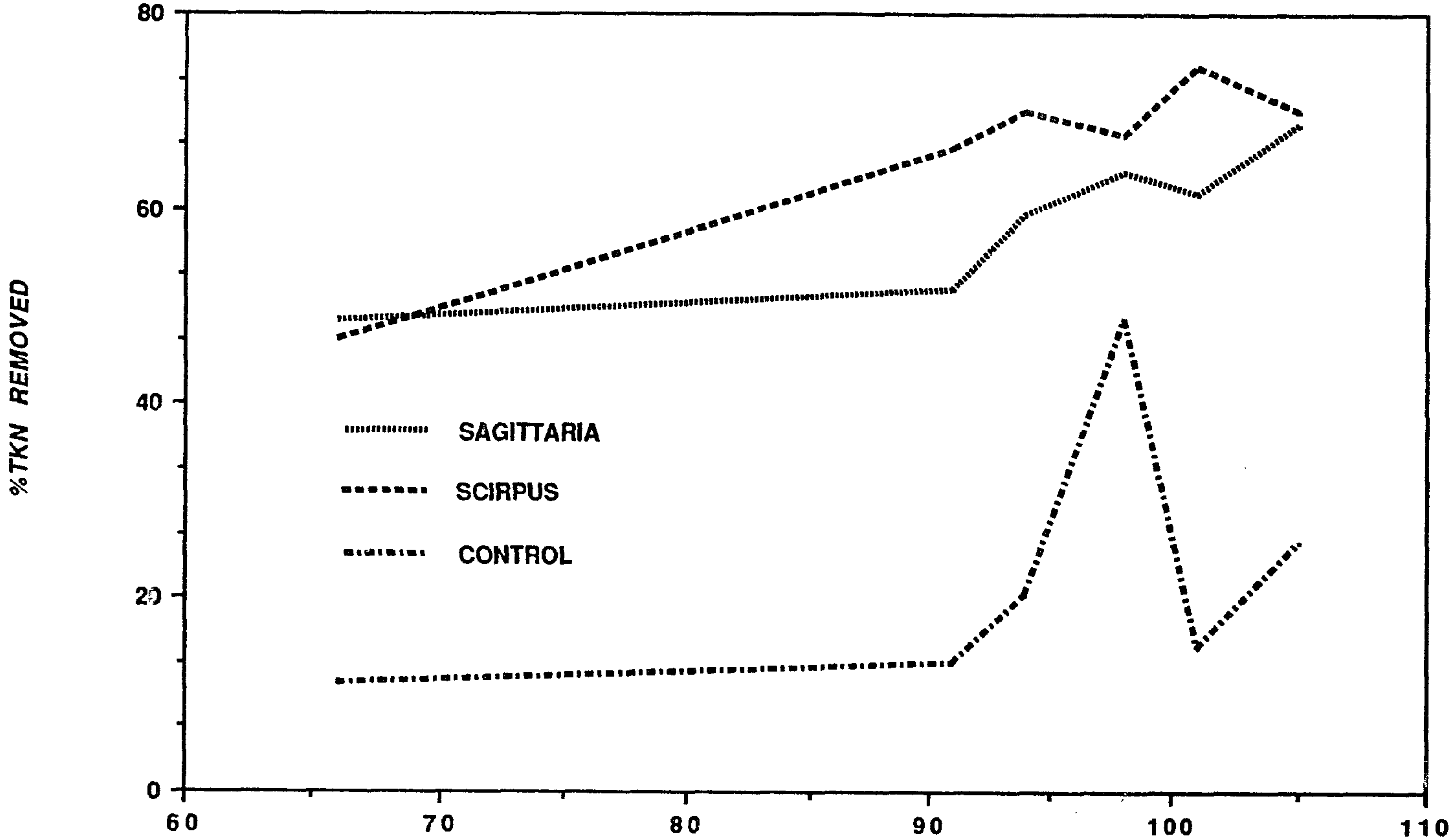
NOTE: Day 20 = May1, 1989

filter systems by COD removal was substantiated by the pH measurements for each system. A larger drop in pH throughout the system indicates microbial activity due to the organic acids or CO_2 produced by microbial metabolism. For the systems containing plants, the pH of the effluent was consistently between 7.2 and 7.7, while the feed water and control effluent pH consistently ranged between 7.6 and 8.7, with the control having a higher pH than the feed water on several days. Higher pH readings than the feed water was probably due to the presence of algae on the surface of the control filter.

Similarly, mass percent TKN removals, shown in Figure 1.4, were enhanced by the systems containing plants. Within the dried plant tissue, Sagittaria contained essentially the same percentage of TKN (25 mg N/ g dry plant weight, average) as the Scirpus (22 mg N/g dry plant weight, average). Due to the higher moisture content of the Sagittaria (91%) compared to Scirpus (84%), however, the total mass of Kjeldahl nitrogen was higher for the Scirpus (50 g) as opposed to the Sagittaria (36 g).

The final parameter of significance in the preliminary analysis was oxidation-reduction potential (ORP), which is a function of the Gibbs free energy of a reaction and is an indication of the reactions taking place within the system. Certain reactions are characteristic of particular ORP value ranges; for example, below approximately +350 mV

FIGURE 1.4 - MASS %TKN REMOVED VS TIME
DURING PRELIMINARY EXPERIMENT



NOTE: DAY 60 = June 10, 1989

ORP, oxygen will not be present since it is completely reduced to water below this point. ORP measurements taken near the influent and effluent one-third of the three filter systems indicate each of the systems, with negative ORP values, were well into the anoxic range. Dissolved oxygen (DO) profiles within the systems also revealed an absence or negligible (<0.5 mg/l) amount of DO at any depth on either end of each system. An earlier DO profile taken when the flow was 500 to 1000 ml/min, in recycling-flow mode, showed around 1 mg/l near the surface of the water level decreasing to 0.5 mg/l or less near the bottom of the tank for each system. An increase in organic loading at the end of this preliminary study resulted in a decreased ORP in both ends of each system, as expected. The plant systems appeared to maintain a higher ORP, at least at lower organic loadings. This is probably due to the oxygen known to be transferred from the shoots to the roots within aquatic plants. This action creates a thin aerobic zone in the root area, too thin to be directly measured by this study, but significant enough to perhaps raise the overall ORP 10 to 100 mV.

Section 4.2: Eighty-Day Variable Loading Investigation

On August 26, 1989, the 80-day experiment began, using four influent BOD_5 concentrations at two flow rates (8 combinations) lasting 10 days each. Average BOD_5/COD values for each 10-day period are listed in Table 1.2.

Taking into account experimental error, the values in Table 1.2 justify the use of COD as a representative parameter for BOD_5. Results of the 80-day experiment showed that, during the 80 ml/min flow, the average percentage of COD mass removals were 70%, 56%, and 42% for the Scirpus, Sagittaria, and control systems, respectively. This performance ranking, which is identical to the preliminary experiment, was consistent during this first half of the 80-day experiment except during the first 10 days, as shown in Figure 1.5. Prior to beginning the 80-day experiment, the feed tank was cleaned with dilute Clorox and rinsed thoroughly. This operation took 24 hours, during which the water level in the tanks containing plants dropped approximately one foot. Subsequently, a considerable die-off in the Sagittaria system occurred, although the Scirpus system appeared unaffected. Root damage and loss of dead plant matter through the effluent may have accounted for the increase in COD (and BOD_5) over the first ten day period in the Sagittaria system. In addition to poorer performance, variability in performance was greater in the control system. Standard deviations for the Sagittaria, Scirpus and control systems were 8.7%, 9.6%, and 12.6%.

At the higher flow, the average percentage of COD mass removals were 68%, 59%, and 52% for Scirpus, Sagittaria, and the control, respectively. Although the system

TABLE 1.2. Average BOD_5/COD Ratios

Flow (ml/min)	BOD5in (mg/l)	Influent	Sagittaria Effluent	Scirpus Effluent	Control Effluent
80	28	0.31	0.30	0.29	0.38
80	78	0.45	0.29	0.36	0.40
80	107	0.37	0.43	0.43	0.48
80	51	0.53	0.43	0.43	0.50
140	28	0.29	0.36	0.34	0.32
140	78	0.45	0.42	0.42	0.38
140	107	0.24	0.34	0.42	0.33
140	51	0.48	0.31	0.43	0.42
AVG		0.39	0.36	0.39	0.40
STD DEV		0.10	0.06	0.05	0.06

FIGURE 1.5: %COD Removed - 80 ml/min Flow Rate

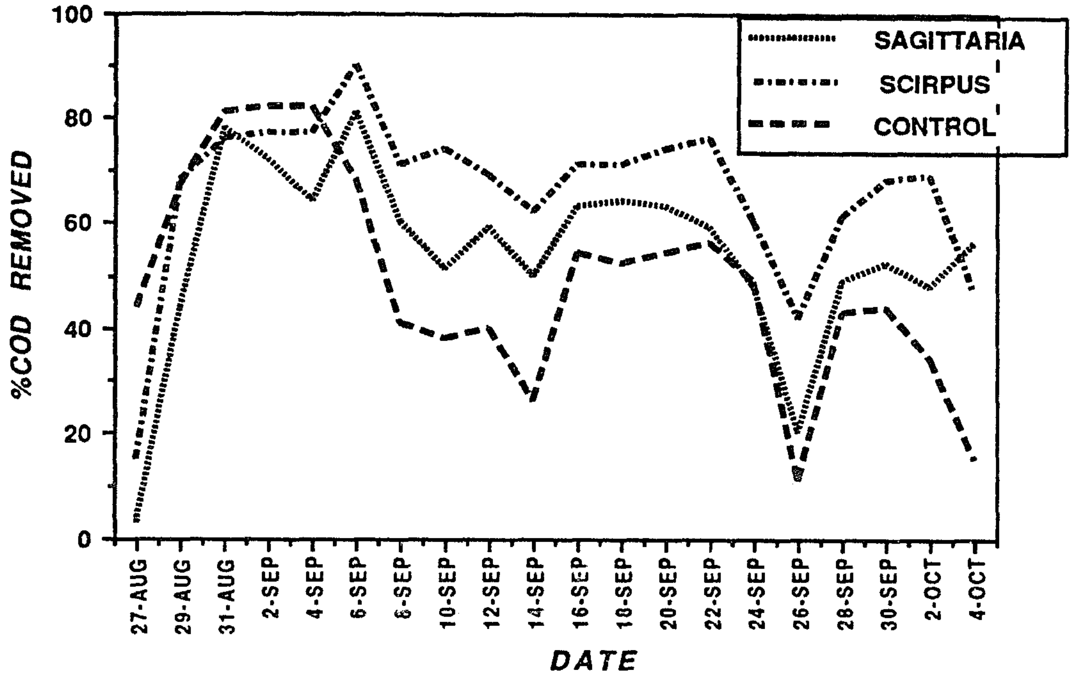
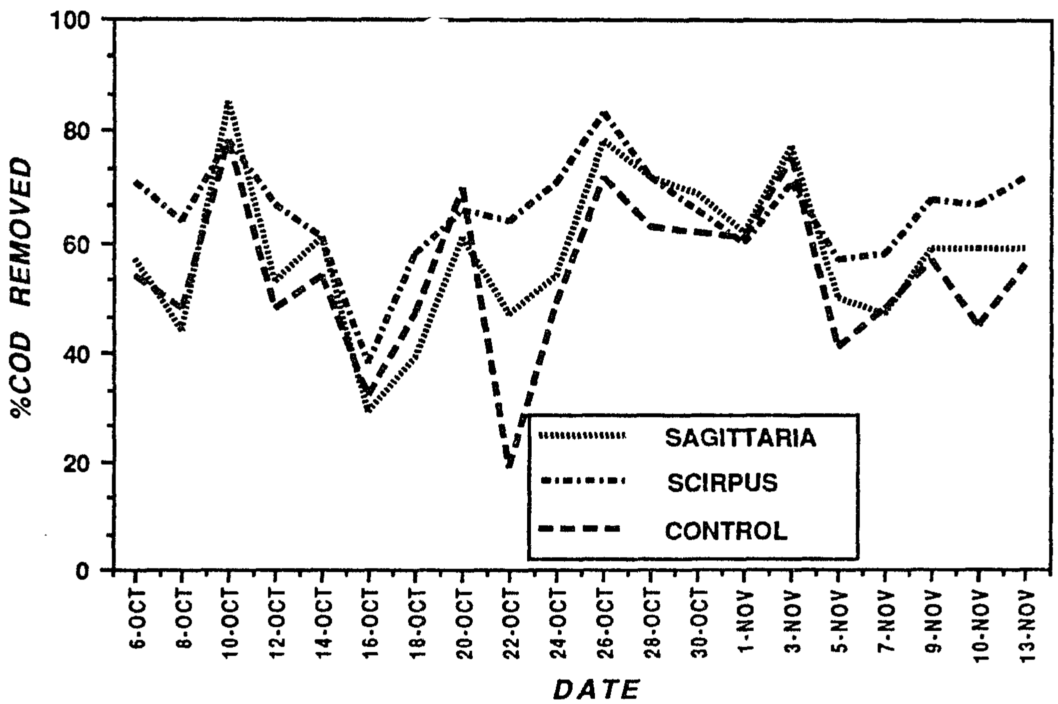


FIGURE 1.6 : %COD Removed - 140 ml/min Flow Rate



performances were more equivalent at the higher flow, the relative system performances noted previously are still valid, as shown in Figure 1.6. Likewise, the variability in the control was again higher than the vegetated systems with standard deviations of 7.7%, 6.5%, and 15.3% for the Sagittaria, Scirpus, and control.

To evaluate the relation between influent organic mass and organic removal, the influent COD mass was plotted against the mass percentage of COD removal for the average of the last three days of each 10 day period. As shown in Figures 1.7 and 1.8 for the 80 and 140 ml/min flow respectively, there was not a strong correlation between influent COD mass and percentage of COD removed in any of these systems. Averages of the last three days are plotted on these figures; although the regression calculations were based on individual daily COD data. These graphs also suggest differences between the three systems, although at the higher flow these differences appear to be merging. It should be noted that, during the higher flow portion of the study, the number of daylight hours decreased by approximately 2 hours per day and the water and air temperatures dropped by approximately 5°C. Decreased sunlight and temperatures lower plant productivity and, therefore, may decrease the performance enhancement produced due to the plants. Likewise, lower temperatures, in the range found in this study, produce slightly less

FIGURE 1.7 - Influent COD Mass vs %COD Removed
80 ml/min Flow Rate

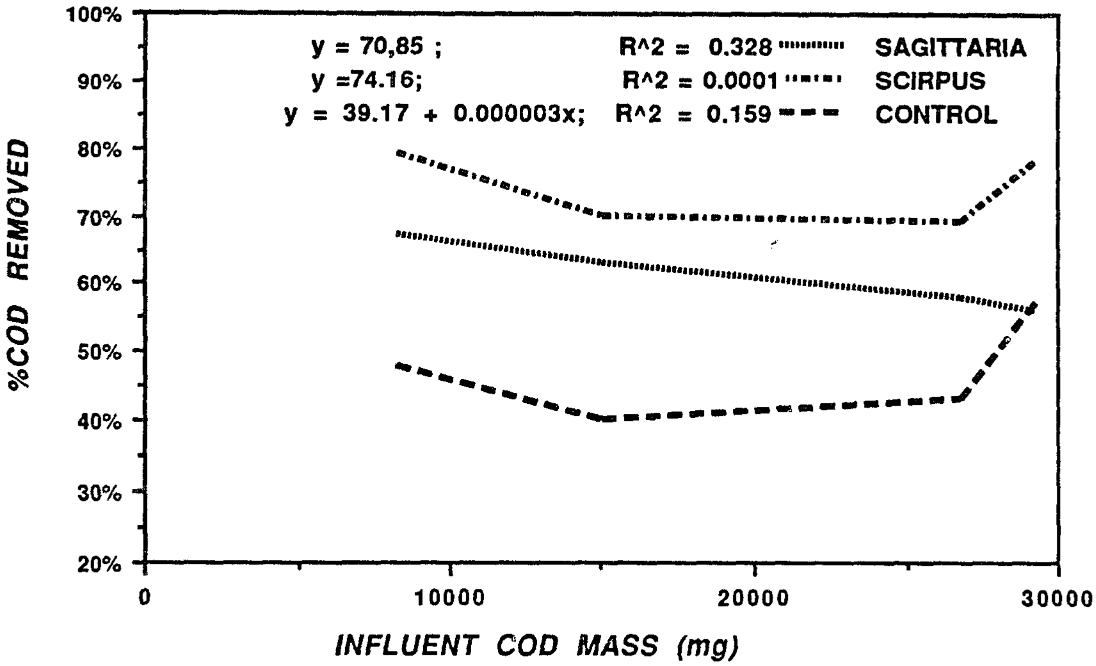
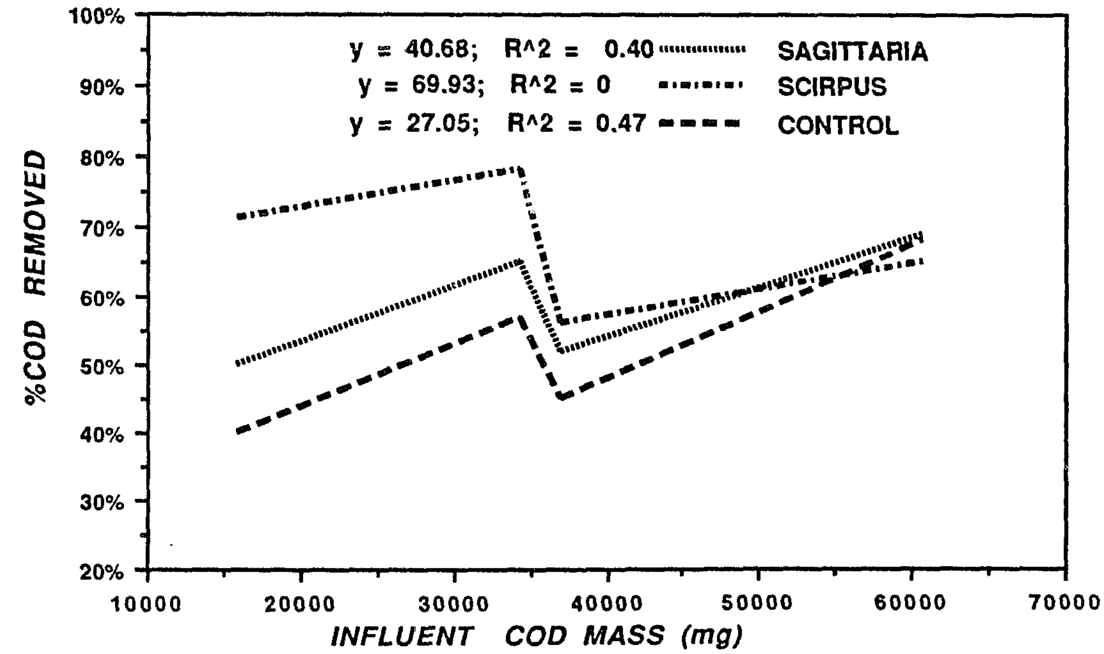


FIGURE 1.8- Influent COD Mass VS%COD Removed
140 ml/min Flow Rate



microbial activity. Other factors that could tend to equalize the systems under the higher flow conditions include decreased adsorption by the plant roots and greater outflow of degraded plant material.

As noted in the preliminary period above, ORP measurements during this 80-day experiment were below -200 mV at all times. This indicates an absence of dissolved oxygen since oxygen gas is completely reduced to water below +350 mV. Random dissolved oxygen readings confirmed a negligible level of oxygen.In addition to its relation to oxygen content, ORP was monitored to determine its suitability as an estimating parameter for organic removal. A lack of correlation, however, between ORP and the COD mass percentage removal nullified this use of the easily measured ORP.

Although the ORP and DO measurements indicate anoxic conditions in these systems, nitrification may occur in the thin aerobic zone surrounding the root systems, which is discussed in Section 2.3 of Part Two. Another path of nitrogen removal within a rock-plant filter is ammonia or nitrate uptake by the plants. Nitrogen removal by ammonia stripping is unlikely at the neutral pH range and ambient temperatures existing within most rock-plant filters.

Enhancement of nitrogen removal by the vegetated systems as compared to the control is suggested by the overall average TKN percentage removals (based on mass) of

19%, 32%, and 10% for the Sagittaria, Scirpus, and control systems, respectively. The 10-day average TKN mass percentage removed for the 80 ml/min flow and the 140 ml/min flow are graphically illustrated in Figures 1.9 and 1.10, respectively. The average TKN removal percentages (mass basis) at the lower flow were 18% and 28% for the Sagittaria and Scirpus systems, respectively, compared to only 1% in the control system. At the higher flow, the Sagittaria system had a TKN removal of 17%, which was equivalent to the 18% removal in the control, and the Scirpus system had a 34% TKN removal. This trend for a lesser degree of difference between the plant systems and the control system at the higher flow agrees with the COD results.

Other researchers have also noted the increased removal of nitrogen in vegetated filters as compared to unvegetated filters. Davies and Hart (1990) noted a nitrogen removal increase from 3% in unvegetated, submerged gravel beds to 10% in identical beds vegetated with reeds. After aeration of a section of each bed, the nitrogen removal rose to 22% to 24% in both planted and unplanted beds.

In another study by Hofmann (1990) using reeds (Phragmites australis) to improve treatment in sludge drying beds, several parameters indicated increased nitrogen and organic removals in the reed bed due to

Figure 1.9: %TKN Removed - 80 ml/min Flow Rate

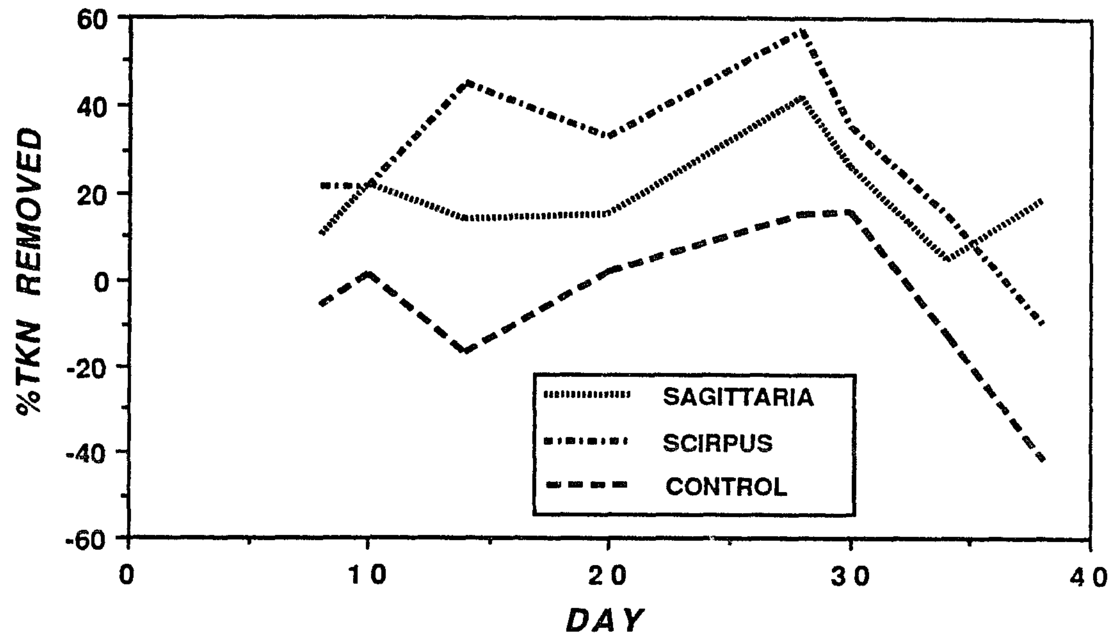
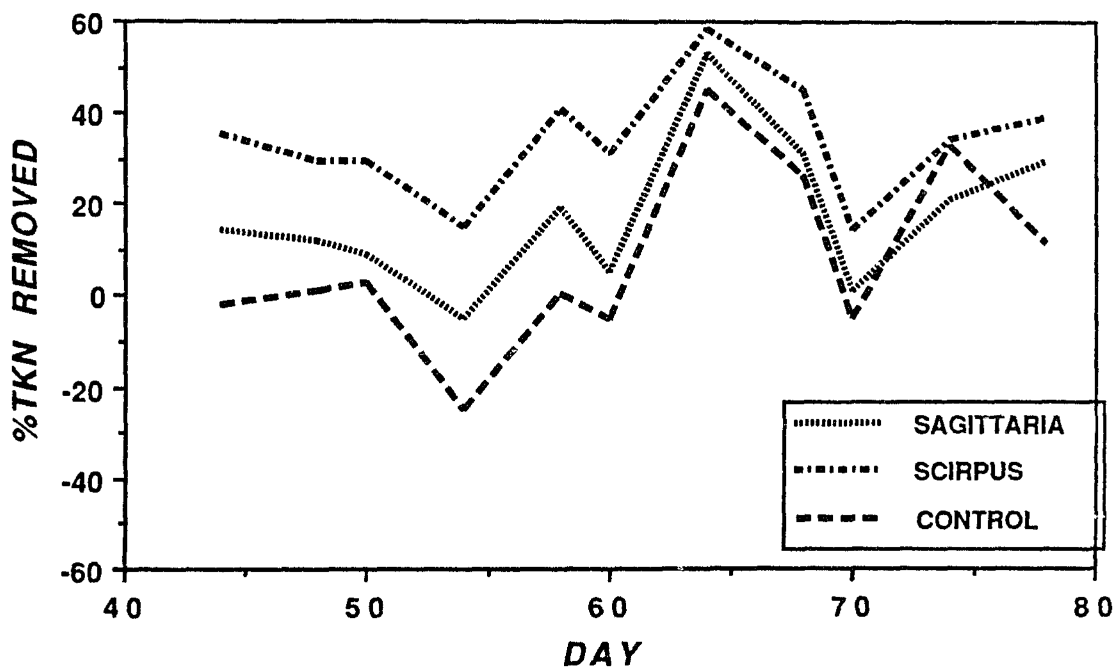


Figure 1.10: %TKN Removed - 140 ml/min Flow Rate



localized aerobic zones. Leachate oxygen concentrations and oxidation-reduction potential (ORP) readings from an aerobic stabilized sludge were higher in the reed bed (4.5 mg/l and +328 mV, respectively) than the control (1.7 mg/l and +226 mV, respectively). In addition, ORP readings within the beds were higher in the reed bed, particularly in the lower layer. The nitrogen mass balance reported by Hofmann (1990) indicated the mass of nitrogen oxidized to nitrate was more than twice the mass of nitrogen removed by plant uptake as ammonia or nitrate. This suggests nitrification/ denitrification is a more significant nitrogen sink than plant uptake.

Chapter 5
DISCUSSION

Results of this bench-scale study were similar to BOD_5 removals found by Gersberg, et al. (1986) in their outdoor pilot-scale study at the Santee Water Reclamation Facility in Santee, California. The wastewater source in this pilot-scale study was primary wastewater which flowed through trenches at a rate resulting in a 6 day retention. BOD_5 removals found by Gersberg, et al. were 96%, 81%, 74%, and 69% for *Scirpus, Phragmites, Typha,* and control systems, respectively; which gives a 39%, 17%, and 7% increase over the control system in the *Scirpus, Phragmites, and Typha* systems. In the bench-scale study described herein, approximately 15% and 25% increases over the control were observed for the *Sagittaria* and *Scirpus* systems, respectively; although the average percentages of removal for the three bench-scale systems were lower overall than the percentages found by Gersberg, et al. The BOD_5 removal percentages found in the bench-scale study were also slightly lower than those cited by Wolverton (1987) from a 6 or 7 day retention time artificial wetland. Removal rates obtained by Maddox and Kingsley (1989), however, in their 2.3 to 5 day retention time filter which contained sand and *Eleocharis dulcis* (Chinese water chestnut) and received livestock waste were nearly identical to the removal rates found in this bench-scale study. Other COD removal data similar to this bench-scale study was reported by Wood and Hensman (1989) who treated septic sewage in their gravel and Arundo donax, 2.5 day retention time filters.

The other major parameter of importance in this investigation was nitrogen removal. Since organic nitrogen was the primary nitrogen source in the synthetic wastewater, ammonia removals are not comparable to other studies because organic nitrogen transformed into ammonia within the filters which raised the effluent ammonia concentration higher than the influent, where very little ammonia was present. Gersberg, et al. (1986) found ammonia removals up to 94%; however, Wood and Hensman (1989) noted only an 18% ammonia reduction in their gravel-filled filter planted with Arundo donax receiving septic sewage. Although not directly correlated to ammonia removal, the TKN removal rates measured in the bench-scale study were as high as 45%, which falls between the ammonia removal rates found in the above two studies.

Root zone comparisons between the bench-scale study and the field study by Gersberg, et al. (1986) showed deeper root systems in the field study. Gersberg, et al. measured root zones on the Typha, Scirpus, and Phragmites plants to be 12", 24", and 30" deep. In the bench-scale study, the root zones of both the Scirpus and Sagittaria plant systems were approximately 12". Although the depth of both sets of filters was equal (30"), the location (indoor vs.

outdoor) and water levels may have been the difference. Another observation made during the disassembling of the bench-scale systems was the presence of a black, gelatinous mass which filled the pore spaces in the influent quarter of each system. This accumulation is most likely bacterial growth, iron sulfide precipitate, or a combination of the two and may contribute to clogging problems experienced by several large, municipal rock-plant filter systems.

Chapter 6
CONCLUSIONS

From this bench-scale study, the following conclusions were drawn:

1. Oxidation-reduction potential measurements and dissolved oxygen readings indicated that the filter systems analyzed in this study were anaerobic throughout.
2. COD data generated by this study indicated the plant systems were superior in removing organic material compared to the unvegetated system. Overall, organic removals averaged roughly 60%, 70%, and 50% for the *Sagittaria, Scirpus,* and control systems, respectively.
3. The correlation between COD mass applied and COD mass percentage removed under the conditions of this study was very low. There was, however, a greater difference in removal rates between the systems during the 80 ml/min flow than during the 140 ml/min flow.
4. During the 80 ml/min flow, TKN removal rates in the *Sagittaria* and *Scirpus* systems were 17% and 27% higher, respectively, than the 1% average TKN removal rate found in the control system. Similar values for the 140 ml/min flow were 0% and 16% higher than the 18% average TKN removal rate found in the control system. As noted in the organic removal calculations, TKN removal percentages revealed a greater difference

in removal rates between the systems during the 80 ml/min flow than during the 140 ml/min flow.

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PART TWO: THE MODEL

Chapter 1
INTRODUCTION

The purpose of a mathematical model is to bridge a gap between the real world and abstract mathematical entities. In contrast to physical systems, mathematical models offer a method of rapidly and inexpensively analyzing a great number of process variations. Most mathematical models cannot approach the complexity of the systems they emulate; however, in order to design a system for many different environments, mathematical simulation is a valuable design tool.

The first step in creating a model is resolving the degree of complexity to build into it. This degree of complexity is a function of the system characteristics, available information supporting the model, and the application intended. Rock-plant filters are complex systems involving several interacting subsystems such as the plants, the microorganisms, system hydrology, and physical processes (e.g., sedimentation and adsorption). A relative lack of historical data for developing the model, however, requires simplification of the model. In addition, to achieve general applicability of the model in various potential locations, the model should require only readily available input. As for the application of the rock-plant filter model to be developed in this document, the objective is to determine optimal rock-plant filter dimensions in order to meet discharge permit limitations of 5-day biochemical oxygen demand (BOD_5) effluent concentrations. Although suspended solids limits are also stipulated in discharge permits, suspended solids entering a rock-plant filter should be minimized to avoid clogging. By using primary settling and algae prevention or removal techniques, solids entering the filter will be minimal. Additionally, some permits dictate ammonia-N limits. Reported nitrogen removal rates are inconsistent, however, there is a general consensus among researchers that a horizontal flow, flooded filter will not produce appreciable nitrification due to low oxygen levels (e.g., Davies and Hart (1990), Willadsen, et al. (1990), Watson, et al. (1990), Schierup, et al. (1990), Bucksteeg (1990)). Research is currently being conducted on alternate aquatic plant system designs, such as the vertical flow filters proposed by Brix and Schierup (1990), to ameliorate this problem. The horizontal flow, flooded filter is, however, very conducive for denitrification. For these reasons, BOD is considered to be the limiting design factor for sizing a horizontal flow rock-plant filter and, therefore, only factors significantly affecting BOD are considered in the model.

Chapter 2
LITERATURE REVIEW

Although no firmly established design model exists for rock-plant filters, there are several methods in use. In the first part of this section, these methods will be discussed. Following the discussion of current design methods, this literature review will cover the three aspects of the submodels comprising the model developed herein. These three aspects are: hydrology, plant growth, and the removal kinetics of BOD-producing compounds.

Section 2.1: Rock-Plant Filter Design

Currently, many rock-plant filter systems are designed on a hydraulic basis alone. Depth of rocks arbitrarily varies from 1 to 2-1/2 feet with the width being determined by Darcy's equation for flow through a porous media:

$$w = Q / dkS \tag{1}$$

where:
- w = filter width, L
- Q = average flow rate, L^3/T
- d = filter depth of submergence, L
- k = hydraulic conductivity, L/T
- S = hydraulic gradient, L/L

The length is then determined by specifying a hydraulic detention time for the filter, accounting for porosity. Popular detention times specified are from 24 hours to 6 days, although no solid scientific basis supports any particular detention time. Hydraulic conductivity measurements have also not been thoroughly investigated. Cooper and Hobson (1988) indicate a hydraulic conductivity of 10^{-3} m/s or more is applicable for a gravel bed; however, Boon (1985) notes that the horizontal velocity should not exceed 10^{-4} m/s, regardless of the slope, to avoid disruption of the medium-rhizome structure and to allow sufficient contact time for treatment. According to Hobson (1989), the relation between hydraulic conductivity and gradient is important in determining the width of reed bed treatment systems; however, avoiding surface flow across the bed is an equally, if not more, important hydraulic concern. Hydraulic conductivities listed by Hobson (1989) for gravel beds range between 10^{-4} and 10^{-1} m/s, but he discourages sloping the filter bottom due to the increased likelihood of initiating and maintaining a surface flow and the greater difficulty in controlling the water level. Particularly in gravel beds, Hobson suggests a hydraulic gradient as low as 1% and a flat bottom slope to encourage a more even water level and, therefore, an equal growth of plants throughout the bed.

In addition to the uncertainties in quantifying the hydraulic conductivity, this value will change over time as wastewater sediments settle, plant detritus builds up, and plant roots fill the void spaces. Plant root growth may also increase the permeability by disturbing the solids built up in the pore spaces. Watson, et al. (1989)

speculate that the plant roots may be critical in maintaining an adequate long-term hydraulic conductivity. This phenomenon, however, is associated more with soil rather than gravel beds. In sand systems, Trautmann, et al. (1989) investigated changes in hydraulic conductivity over a 7-month period in both nonvegetated systems and systems vegetated with Typha glauca Gadr and Scirpus acutus Muhl contained in boxes in a greenhouse. The saturated hydraulic conductivity declined by 41% in the control systems (due to sand settling, according to Trautmann, et al.) and by 55% in the vegetated systems. No research was found, however, indicating the reduction of hydraulic conductivity in a gravel bed, with or without plants.

Another design procedure, which is the current method described in the United States Environmental Protection Agency (EPA) design manual written by Crites, et al. (1988), recommends using a depth consistent with the reported root depths of various aquatic plants. The most frequently referenced experiment for typical root depths was conducted at Santee, California by Gersberg, et al. (1986). The bulrush root depth found by Gersberg, et al. in Santee, however, were twice as long as those found in the bench-scale experiment described in Part One, using the same filter depth. Root depth, according to Lawson (1985), is controlled by water level and, therefore, is not a concrete basis for selecting a filter depth. Lawson (1985) further points out that manipulation of the root depth of reeds by adjusting the water level occurs only during the first 2 to 4 years, after which rhizomes grow horizontally only.

To derive the surface area required, Crites, et al. (1988) recommend first calculating the filter width by Darcy's equation (1) above, although they give hydraulic conductivity for sand only and not gravel. For determining the filter length, Crites, et al. (1988) give the following equation, based on first-order reaction kinetics:

$$l = [Q(\ln C_o - \ln C_e)/(K_T dnw)] \qquad (2)$$

where: Q, w, and d are as stated in equation (1),

l = filter bed length, L

C_o = influent BOD_5 concentration, M/L^3

C_e = effluent BOD_5 concentration, M/L^3

K_T = temperature-dependent first-order reaction rate constant, 1/T

n = porosity of the bed, as a fraction

No data supporting the correlation between actual system performance and calculated system performance were presented by Crites, et al. (1988), although supporting data was presented by these authors for their design equation given for a free water surface wetland system.

Equation (2) above is identical to the design equation given by Watson, et al. (1989) and Reed, et al. (1990) which are respectively upheld by the Tennessee Valley Authority and the Water Pollution Control Federation. Watson, et al. (1989) elaborate on this equation by suggesting the rate constant, K_T, is related to the porosity of the bed media, n, and give the following tentative relationship, proposed by Reed, et al. (1990):

$$K_{20} = 37.31 K_o n^{4.172} \qquad (3)$$

where K_o = the "optimum" rate constant at 20°C for a medium with a fully developed root zone
= 1.839 $days^{-1}$ for typical municipal wastewaters

K_{20} = first-order reaction rate constant at 20°C, 1/days

n = bed porosity, as a fraction

In the definition of K_o above, Reed, et al. (1990) do not explain what is meant by "optimum"; however, the maximum rate of BOD_5 degradation under ideal conditions is implied.

In the United Kingdom, the basis for sizing reed bed treatment systems, which utilize soil or gravel media, are the semi-empirical equations given by Kickuth, according to Cooper and Hobson (1989). For crude or settled sewage, the required filter length is calculated from Kickuth's following equation:

$$l = 5.2Q(\ln C_o - \ln C_e)/w \qquad (4)$$

where l, Q, w, C_o, and C_e are as described in equations (1) and (2) above where the units are meters, meters/day, meters, mg/l, and mg/l, respectively

This equation produces a surface area of around 2.2 m^2 per population equivalent (pe, equivalent to 56 grams of BOD_5 /person/day); however, as suggested by Cooper and Hobson (1989), the area required may be closer to 3 to 4 m^2 /pe. In addition, analyses of 29 gravel/ reed beds in the United Kingdom by Findlater, et al. (1990) conclude the 5.2 factor in equation (4) is closer to 20.

Comparing equations (2) and (4), setting $1/(K_T dn) = 5.2$ results in identical equations, provided agreeable units are used. It should also be noted that both equations (2) and (4) are based on plug-flow conditions and first-order reaction kinetics; however, no supporting investigations accompanied these equations to validate using this type of reaction. One investigation, however, attempted to develop a first-order reaction performance model for an existing system. This was an investigation involving seven field-pilot scale aquatic plant systems filled with gravel or water in Richmond, Australia conducted by Bavor, et al. (1989) over a 3.5 year period. Model analysis in this case consisted of performing regression analyses on the logarithm of concentration values for suspended solids, BOD_5, total organic carbon (TOC), total Kjeldahl nitrogen, ammonia, total phosphorous, and fecal coliforms using the first-order reaction equation:

$$\ln(C/C_o) = -KT \qquad (5)$$

where: C = effluent contaminant concentration

C_o = initial contaminant concentration

K = temperature dependent reaction constant

T = hydraulic retention time

Correlations between $\ln(C/C_o)$ and T were found to be consistently low for suspended solids, BOD_5, and TOC. This low correlation, according to Bavor, et al., is possibly due to insufficient data for estimating contaminant removals in the very active inlet zone, where most of the removal of these parameters took place. Better correlations were obtained for nitrogen components and fecal coliforms. Phosphorous data showed virtually no change in influent and effluent concentrations.

Section 2.2: Hydrologic Models

Components of the hydrologic mass balance of a rock-plant filter system include flows into the system, precipitation, evapotranspiration losses, and flows out of the system. Flows into the system are either measured or estimated, for instance, from the population the system supports. Historical data from local climatological reports is the easiest, and possibly the most accurate, estimate for precipitation. This climatological data also gives Class A pan evaporation, which may be used in estimating evapotranspiration losses in the rock-plant filter system. Flow out of the system is then obtained by summing the other hydrologic components over a specified time, assuming the system water level remains relatively constant.

Of the hydrologic quantities related to rock-plant wastewater treatment systems, estimates of system evapotranspiration rates are the most likely to require future research. Elaborate methods for calculating evaporative losses have been derived; however, most require extensive climatological data which is not available at many locations.

Formulation of evaporative theory began as early as 1802, according to Brutsaert (1982), when Dalton related evaporation losses to wind speed and the difference in actual vapor pressure to the saturation vapor pressure at ambient temperature. By the mid-1900's, evaporative theory developed into two theoretical approaches: mass transfer and energy balance. The latter approach has gained greater acceptance, however, due to the less refined instrumentation required for its implementation. The basic principle behind the energy balance concept is that, since evaporation requires large amounts of heat energy, the rate of evaporation is controlled by the available heat energy, assuming an adequate water supply is available.

In the 1950's, application of theoretical evaporative concepts received major attention after the work of H.L. Penman. Penman (1948) combined Dalton's relation, the energy balance equation, and the Bowen ratio (sensible heat flux divided by the evaporation rate); however, this equation requires knowledge of the saturation water vapor pressure, temperature of the air and surface, atmospheric pressure, net solar radiation, and mean wind velocity above the vegetation. All of these values are not typically known at many locations; therefore, general application of this equation is limited. Thibodeaux (1979) also gives an equation for estimating evaporation rate based on the energy budget, however, his formula requires about a dozen pieces of information on the system.

From a more empirical approach, Jensen and Haise (1963) combined the energy balance equation with field data to derive an evapotranspiration equation for arid and semi-arid rangelands. By neglecting heat flux stored in the system, radiation flux used in photosynthesis, and the sensible heat flux to the ground, Jensen and Haise deducted that the rate of evapotranspiration divided by the short wave radiation flux is linearly related to the mean air temperature. This relationship was demonstrated by linear regression on approximately 1000 evapotranspiration measurements at several arid or semi-arid sites containing various crops. The correlation coefficient for this relation was 0.86; however, preliminary investigations in other semi-arid and more humid zones indicate higher evaporation rates than estimated may be obtained in extremely windy conditions. Furthermore, this relation does not apply to areas containing new growth or freshly harvested vegetation. This technique, however, would be useful in deriving a similar relation for wetlands.

Strictly empirical methods of estimating transpiration include the equation proposed by Bernatowicz, et al. (1976) which introduces a transpiration coefficient characteristic of the species of plant. Mean coefficient values found in their study involving _Phragmites australis, Schoenoplectus lacustris, Typha augustifolia, and Typha latifolia_ were 391.0, 690.6, 499.8, and 421.9 grams of water transpired per mean dry weight of plants in grams, respectively. These values are dependent on location since the transpiration coefficient for _Phragmites australis_ was 320 in the reed-belt, whereas the above values were taken on land.

Kadlec (1989a) discusses several other methods of estimating evapotranspiration in wetlands. Perhaps the simplest of these methods consists of multiplying the Class A pan evaporation from an adjacent open site by 0.8. Based on data from a variety of locations, this multiplier appears to be independent of climate and is, therefore, feasible for general applications provided the climatological station is relatively close to the filter system site.

Another evapotranspiration estimation method mentioned by Kadlec (1989a) is based on evidence that approximately half of the net incoming solar radiation impinging on a wetland is converted to water loss on an annual basis. For the purposes of the rock-plant filter design model, however, reasonable accuracy on at least a monthly basis is necessary.

Factors to be considered when estimating evapotranspiration in a wetlands include seasonal variations and the size of the wetland. Seasonal patterns effect both radiation and vegetation patterns which subsequently produce seasonal evapotranspiration patterns. One method of building vegetation patterns into the evapotranspiration equation is through the use of a crop coefficient multiplied by the annual average evapotranspiration rate, according to a reference cited by Kadlec (1989a); this multiplier effectively enhances losses during the summer and decreases evapotranspiration losses during the winter.

In addition to seasonal variations, the size of the wetland may require adjustments to the estimating equation. As discussed in Monteith (1976), advection can cause what is known as the "clothes-line effect" in small wetlands which increases evaporation because of ventilation through the vegetation. How small the wetland can be without experiencing this phenomenon is uncertain.

Factors that are apparently not important in calculating evapotranspiration within wetlands, according to evidence presented by Kadlec (1989a), are the type of vegetation and the energy associated with incoming wastewater. Monteith (1976) also concludes that the type of vegetation is insignificant when estimating the evapotranspiration rate in summer as well as winter.

The survey of evapotranspiration measurement techniques detailed above illustrates the possibilities for estimating this parameter in future models and indicates the methods explored in deciding on a method to use in this model. Compromising between data typically available and the need for accuracy, the local Class A pan evaporation multiplied by 0.8, as discussed by Kadlec (1989a) will be used in the following model development.

Section 2.3: Plant Growth Models

Once the flow rates into and out of the rock-plant filter system are quantified, BOD concentrations can be converted to masses. At this point, the significant sources and sinks may be identified to predict the effluent quality. In Part One, the plants enhanced the mass removal of BOD_5 roughly 10% to 20%. Similarly, Gersberg, et al. (1986) found a BOD_5 removal enhancement of over 30% for their bulrush-rock filter over the control filter. Since plants do not absorb appreciable amounts of carbon through their roots, as indicated by Thornley (1972), this enhancement must be caused by increased aerobic degradation stimulated by oxygen loss through the root system and/ or increased adsorption of organic particles onto the roots. Radial oxygen loss through root tips of aquatic plants, a phenomenon noted by many researchers (e.g., Armstrong (1964), Hook and Crawford (1978), Michaud and Richardson (1989), DeBusk, et al. (1989) and Grosse (1989)), may provide an aerated environment for root-based microorganisms. This phenomenon would greatly increase BOD reduction rates over the anoxic degradation. Evidence against this degradation enhancement, however, is noted in research by Brix (1990) which concludes that, although there is an oxygen flux into <u>Phragmites australis</u> roots growing in a soil bed receiving domestic sewage, root respiration activities almost perfectly balances this influx of oxygen. Thus, concludes Brix, there is no net oxygen loss available for aerobic BOD degradation and microbial nitrification. Hofmann (1990) and May, et al. (1990), however, located significant quantities of aerobic bacteria, including nitrifiers, on root rhizosphere surfaces within sludge beds planted with reeds and gravel reed beds, respectively. In fact, Hofmann (1990) found one billion more strict aerobic heterotroph's per gram in the reed rhizosphere than in the aerobically stabilized sludge. Root growth, therefore, is considered an important factor in calculating BOD degradation in the model developed in the next section.

In addition to this enhanced degradation, decaying plant matter is a source of organic matter within the system, particularly if plants are not harvested. For these reasons, a model for plant growth, death, and decay which separates above and below ground biomass is needed.

Various models have been developed for natural wetlands; however, caution must be used in applying these models to wastewater-fed, constructed rock-plant filters. Natural wetlands use native soils as the media through which subsurface water flows, hydraulic boundaries are not normally well-defined, surface flows are commonplace, nutrient deficiencies may limit plant growth, and the vegetation is a combination of various aquatic plants types. By comparison, rock-plant filters use 1" and larger gravel as the typical filter media, infiltration and inflows are prohibited by a liner resulting in a very defined hydraulic system, design of the filter should avoid ponding or surface flow, nutrient limitations are rare, and the vegetation is usually limited to one or two species of emergent aquatic plants. These dissimilarities between natural wetlands and rock-plant filters create differences in the kinetics of plant growth and organic degradation. For example, Kadlec (1989b) notes that peak standing crop of cattail (Typha) in a wastewater wetland can be three to five times that in an adjacent natural wetland. Aside from these kinetic differences, the basic approach used in other models can be helpful.

Many generalized models are available for such systems as commercial crop vegetation and grasslands; however, as discussed by Mitsch, et al. (1988), natural wetland models have only begun to appear in the last decade and are, thus, less sophisticated than many other types of plant models. Application of wastewater to wetlands is even less explored by modelers.

Extensive work in modelling of wetland responses to applied wastewater has been performed by Kadlec and Hammer who modelled the Houghton Lake Porter Ranch Wetland in Michigan. Their compartmental computer model accounting for the plant biomass effects in conjunction with other nitrogen and phosphorous cycling components at this site is detailed in Kadlec and Hammer (1985). Ten compartments used in this model include: surface water; three layers of soil; root, woody, and annual biomass; standing dead; and woody and annual litter. Each compartment was furthermore divided into three time periods: spring-summer, fall, and winter. Mass balance equations were then given for bushes, annuals, roots, standing dead, annual litter, woody litter, and peat. Although the model could get very complex from here, Kadlec and Hammer (1985) assume the rates of growth and death to be simple, linear time functions with parameters determined from easily obtained field data. Ratios such as root to shoot ratio and summer to winter decay rates were also used for simplification.

In a later publication, Kadlec and Hammer (1988) employ the same compartmental model and the same site, but the mass balances are performed for surface and interstitial ammonia, phosphate, and chloride concentrations as well as solids in the top- and mid-soil compartments. This approach, although it uses the vegetation kinetics found in the former model, is aimed more at the fate of nitrogen and phosphorous, or the effect of wastewater on nutrient cycling. Numerical integration and finite difference techniques were utilized in accomplishing this objective. Time- and spatial-steps in these calculations were varied according to the rapidity of the mechanism being considered. For instance, a coarse spatial grid was used for interstitial water and solids compartments; whereas, a finer spatial grid was more appropriate for the rapid transactions occurring within the surface water. Likewise, a shorter time-step was used for surface and interstitial water while the relatively stationary biomass and soils compartments were given a longer time-step. It is important to note that the water compartment reactions were treated as if each compartment were a well-mixed cell. Good agreement between field data and model simulation were found in each compartment by Kadlec and Hammer (1988), using more than six years of supporting data; however, this model has no provision to adjust for other locations.

To circumvent the problems of applying a site-specific model to remote places, the model developed by Morris (1982) for Spartina Alterniflora was investigated. Although this model is for a different species than those considered in the rock-plant model, Spartina species are similar to the Scirpus species commonly used in rock-plant filters since both are perennial wetland grasses. Morris's model, which are detailed in the following section on model development, incorporates such parameters as latitude, sun angle, solar radiation, leaf nitrogen concentration, and air temperature. These parameters serve to customize the model for other locations and nutrient levels.

The basis for Morris's model is that dark respiration is a function of air temperature and live plant biomass and gross production depends on air temperature, leaf biomass, solar radiation, sun angle, and leaf nitrogen concentrations. In the model, the response of gross production to leaf nitrogen is assumed to be hyperbolic. Similarly, solar radiation is assumed to be hyperbolically related to gross production. Air temperature, however, is best described by a linear relation with gross production. The independent responses of these variables and the independence of the weight specific rates of dark respiration and gross production underlies the premise from which Morris derived his model. Water deficit is not considered in this model; however, rock-plant filters should never be limited by water since there is a constant inflow. Calibration of the Morris model was afforded by a growth experiment consisting of eight combinations of shade and nitrogen treatments in four hydroponic cultures over one growing season. Subsequently, the model was verified with outdoor hydroponic cultures, as discussed by Morris, et al. (1984). When growth rate predictions agreed well with direct measurements from the cultures, simulation predictions were compared to field measurements in three real marshes: Sapelo Island, Georgia; Flax Pond, New York; and Great Sippewisset Marsh, Massachusetts. Correlation between these measurements and the model were not as high as for the hydroponic cultures, particularly for the Great Sippewisset Marsh; however, there are difficulties in acquiring replicable field measurements of quantities such as belowground biomass. In the hydroponic cultures, this parameter is easily measured; whereas in the natural wetland, it is very difficult, if not impossible, to accurately quantify. Particularly since conditions in rock-plant filters are very similar to hydroponic cultures, the low correlation for natural wetlands does not discredit the model in a rock-plant filter application.

Section 2.4: BOD Removal Kinetics Models

Models for BOD removal are many and varied. Sawyer and McCarty (1978) state that BOD reaction kinetic studies have established the first-order reaction as the most applicable description of BOD degradation for most practical purposes, unless the microorganism population is still in an active growth phase. Particularly for suspended growth processes, this is the case; however, for fixed films, alternative empirical and theoretical relations have been derived.

Trickling filters are one commonly used fixed film wastewater treatment method which has prompted alternative model development. Popular trickling filter equations include those proposed by Eckenfelder, Velz, and the National Research Council (NRC), as detailed in Clark, et al. (1977) and Metcalf and Eddy (1972). The Eckenfelder and Velz equations are based on empirical constants and the first-order rate equation. By contrast, the NRC equations are strictly empirical, based on an extensive study of operating records from military installations. Considerable differences in the volumes predicted by these models is, at least partially, due to the variance in parameters they focus on (e.g. depth of filter, type of wastewater entering the filter, dependence on temperature, etc.). Thus, even for the vertical flow, trickling filter situation alone, these models produce inconsistent predictions. For this reason and the difference in conditions within the trickling filters as compared to rock-plant filters (e.g., oxygen concentrations and availability, oxidation-reduction states), the trickling filter equations can not be expected to give accurate results for the horizontal flow, flooded situation in the rock-plant filter.

Another common kinetic relation used to describe BOD degradation within biofilms is the Michaelis-Menten, or Monod, equation which is based on an enzymatic degradation reaction. Several researchers (e.g., Williamson and McCarty (1976a, b), Harremoes (1978), Rittman and McCarty (1980a, b, 1981) have clearly demonstrated that substrate-utilization kinetics within biofilms can be accurately described by coupling the Monod equation with the diffusion equation for movement of substrate into the biofilm. This model, however, requires knowledge of the substrate-limiting species as well as the flux-limiting species. Additionally, at some minimum substrate concentration, which can be calculated by methods derived in Rittman and McCarty (1980a), the microbial degradation ceases and no biofilm can exist. Williamson and McCarty (1976a) further proposed the possibility of one species being limiting in the outer biofilm while another species is limiting in the inner biofilm, a condition entitled dual limitation. Rittman and Dovantzis (1983) derive a technique for identifying boundaries of the dual-limitation region and give an algorithm for calculating substrate fluxes within this region. Application of these dual-limitation concepts to soluble BOD removal processes suggest that dual limitation very frequently occurs in BOD removal.

Another determination required by the original substrate flux biofilm model discussed above is whether the film is thin or deep. Rittman and McCarty (1981), however, propose a method of determining the flux of a single, rate-limiting substrate into biofilms of any thickness by using explicit methods for deep film regions and a simple iterative method for shallow regions. The criteria for having deep or fully penetrated kinetics is more clearly defined in a later analysis by Suidan, et al. (1987) by relating substrate-utilization penetration to a new dimensionless rate modulus, Q, which is the ratio of the dimensionless substrate utilization rate at the attachment surface to the dimensionless substrate utilization rate for the bulk substrate concentration. Graphical analysis is then used to analyze the reaction order dependency of the overall substrate flux on the bulk substrate concentration.

The mass transport, steady-state approach to predicting substrate utilization in a biofilm reactor, as discussed above, generally requires information on substrate and microbial species and estimations of biofilm thickness. In addition, various constants must be assumed for implementation of this approach. Due to the diverse nature of domestic wastewater and the inaccessibility of biofilms within a rock-plant filter, this approach was not taken in the rock-plant filter model developed herein to avoid error accumulations and unwarranted complexity. Further investigations for more accurately determining the required parameters may support using this method of predicting BOD reduction in a rock-plant filter in the future, however.

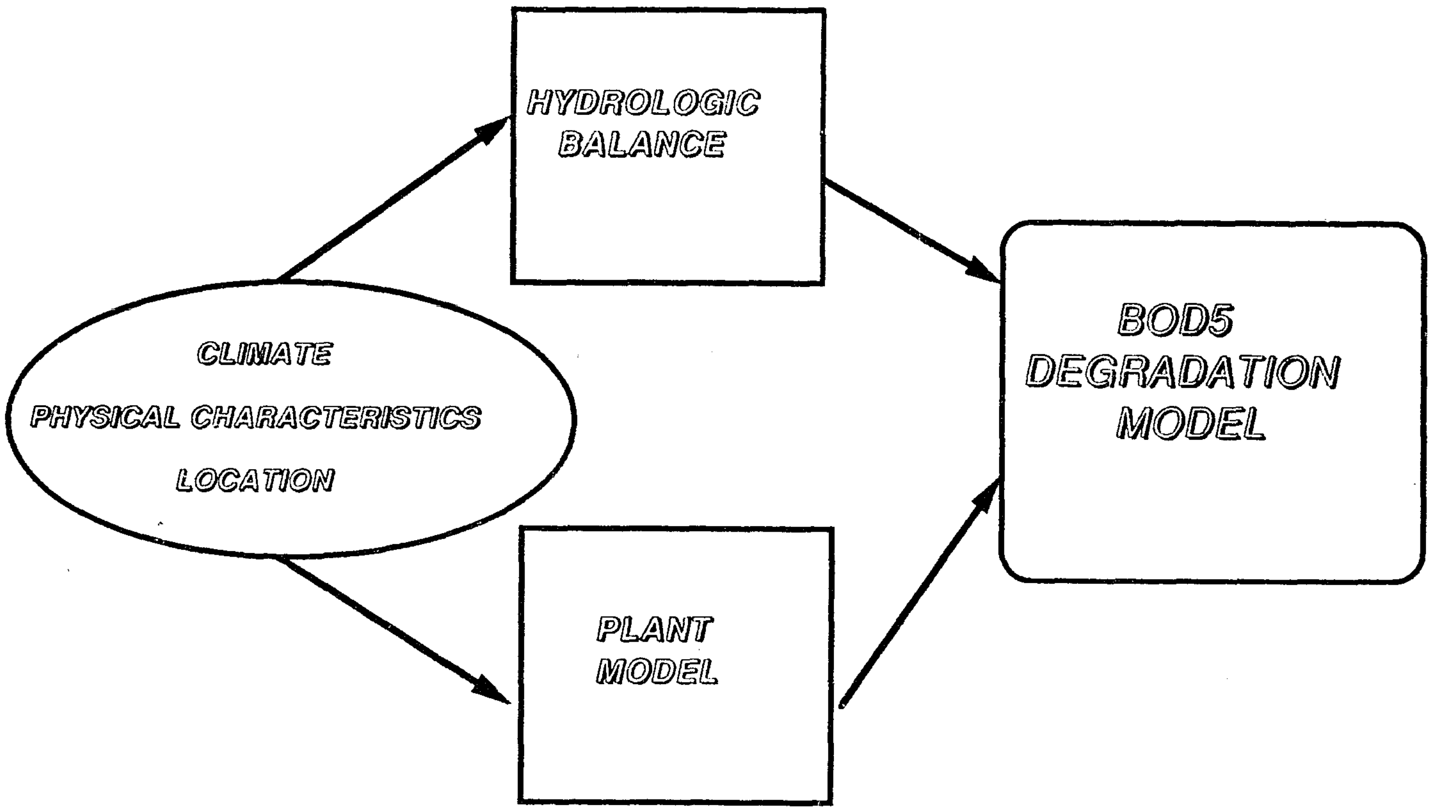
The other form of BOD removal considered in the model is due to settling of suspended BOD-producing compounds. Low velocities within a rock-plant filter (< 2 fps) should allow virtually all of the suspended matter to precipitate. This portion of the total BOD in the influent wastewater will vary, particularly between the synthetic wastewater used in the Part One bench-scale study and a system using actual wastewater. Even for a particular system, this parameter will vary, making predictions by established methods difficult. Common methods of predicting solids removal, as detailed in many texts (e.g., Metcalf and Eddy (1972), Clark, et al. (1977)), rely on a knowledge of particle sizes and densities. The simplest method of predicting this portion of BOD removal is to assume first-order kinetics, or using a multiplier representing the fraction removed by settling. This type of multiplier is used by Reed, et al. (1990) for free water surface wetland systems.

Chapter 3
MODEL DEVELOPMENT

The rock-plant filter model developed in this section is comprised of three sub-models: a water balance submodel, a plant growth submodel, and a BOD removal kinetics submodel. Each of these submodels are interrelated with respect to BOD removal, as illustrated in Figure 2.1. The system water balance is required to convert BOD_5 concentrations to masses so that mass balances may be performed. The plant growth submodel serves two purposes: to estimate root surface mass on which aerobic microorganisms thrive and to determine the quantity of carbon added to the system by decaying plant matter. After defining the hydraulics and plant kinetics, removal kinetics can be applied to predict the BOD_5 effluent concentration. The hypothesis of the overall model is that it can predict BOD removal better than equations (2) and (4) presented in the literature review above by taking into account climatic and plant growth factors.

Unknown parameters within the three submodels were found from the literature and by calibrating with a portion of the bench-scale study data generated in Part One. After validation using the remaining data from the bench-scale study, the model was modified by a finite section approach to better simulate plug flow in larger filters. This modified model was then applied to data from

Figure 2.1: Computer Model Schematic



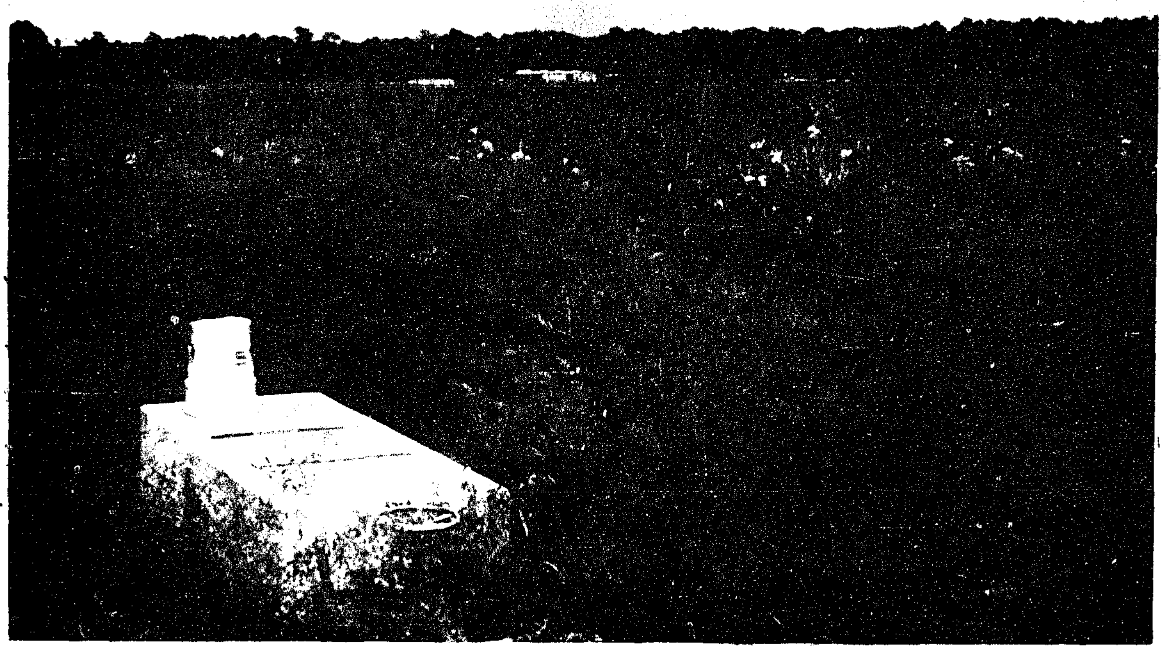
a local full-scale rock-plant filter located in the City of Denham Springs, Louisiana. A view of this full-scale filter is shown in Figure 2.2. Calibration of model parameters which may vary from parameters determined by the bench-scale study data was gained from this application of the model in an outdoor, full-scale situation. Effluent predictions from the full-scale filter were then compared to actual data. This comparison along with predictions from the models presented in the literature review shows the applicability of the model developed here for designing future filters.

Section 3.1: Model Assumptions

Assumptions upon which the model is based include:

* influent wastewater is evenly distributed over the entire width
* Each segment of filter analyzed is considered completely- mixed
* wastewater pH is between 6 and 9 prior to entering the filter
* some type of filter lining (e.g., clay or plastic) inhibits infiltration of groundwater
* plant and microorganism growth inhibitors are negligible in the incoming wastewater
* algae bloom oxygen production and BOD contribution are not considered
* plant growth is even throughout the filter
* adequate phosphorous is present in the influent wastewater to support bacterial and plant growth throughout the filter
* sufficient nitrogen is present in the wastewater to yield at least 1% nitrogen, dry weight basis, in the

Figure 2.2: Denham Springs Rock-Plant Filter - Influent End View



plants throughout the filter

* the only significant sites of microbial degradation occur on rock and root surfaces. This degradation depends on the organic concentration in the bulk liquid and the rock surface area or root mass, respectively. Different rate constants apply to these two degradation sites.

External parameters required by the model include:

* flow rate of influent wastewater
* BOD_5 concentration in the influent wastewater
* air and water temperature
* local precipitation and Class A pan evaporation rates
* estimated initial above-ground plant biomass and BOD5 mass within the filter

Section 3.2: Hydrologic Submodel

The hydrologic mass balance for a rock-plant filter is:

$$\text{flow rate in} + \text{precipitation} = \text{evapotranspiration} + \text{flow rate out} \qquad (6)$$

Influent flow rates are known for the applications described in this report; for applications where influent flow rate is not measured, estimates can be made from population data. In the Part One bench-scale study, precipitation is not a factor and evapotranspiration can be calculated from influent and effluent flow rate measurements, assuming the system water level is constant.

In full-scale, outdoor applications, precipitation and evaporation estimates are obtained from local historical climatological data. This evaporation data is given in Class A pan evaporation rates and will be converted to evapotranspiration within the rock-plant filter by using the 0.8 multiplier discussed in the literature review above. Effluent flow rate is then calculated by the above mass balance.

Section 3.3: Plant Submodel

Net production of plant biomass is calculated as the difference between gross production and respiration. Estimations of these quantities are based on the equation given by Morris, et al. (1984), as discussed in the literature review. These equations are:

gross production $= \rho TNF\sin(\beta)\{\ln[L_i\exp(\alpha B_c/\ \sin(\beta)) + \lambda] - \ln[L_i + \lambda]\}/\ [\alpha(N + \eta)]$ grams(dry)/meter^2/day (7)

respiration $= \rho T(FB_c + B_b)$ grams(dry)/meter^2/day (8)

Where the variables are defined as:

- **B_b** = live, dry biomass of roots and rhizomes (g/ m^2)
- **β** = sun angle over the horizon (radians)
- **B_c** = total dry mass of plant canopy (g/ m^2)
- **F** = quotient of green leaf weight : total canopy weight
- **L_i** = solar radiation incident at top of canopy (mW/ cm^2)
- **N** = nitrogen concentration in dry leaves (%)

T = air temperature (°C)

β and L_i were calculated using equations presented by Sellers (1965). Theoretical solar radiation was scaled down by a 0.56 multiplier which represents the average fraction of maximum solar radiation transmitted to the ground surface. This multiplier was common to three wetland sites, according to least-squares estimation by Morris, et al. (1984). Dry leaf percent nitrogen, N, was found to produce essentially equivalent production rates for N values of 1% to 4%, other variables held constant; therefore, the 4% value was used. In support of this parameter assignment, the level of nitrogen in the Part One bench-scale plants ranged from approximately 1% to 4%.

Constant definitions and values in the model are:

α = solar radiation extinction coefficient

= -0.00034 m^2/g

λ = half-saturation constant for solar radiation

= 30 mW/cm^2

η = half-saturation constant for nitrogen

= 0.36% of dry weight

Ψ = temperature coefficient for gross production

= 0.00071 / °C/ hour

ρ = temperature coefficient for dark respiration

= 2.3E-5 g/g/°C/hr

When the air temperature is less than or equal to 0°C, Ψ and λ are set equal to zero. The constant values listed above were checked in this application using the Scirpus bench-scale system data. The optimized values of these constants, as obtained by sum of squared residuals minimization, are within the range specified by Morris, et al. (1984).

Net production quantities calculated from the above equation are used to estimate changes in the five quantities listed below, where d["parameter"] is the change in "parameter" over the timestep, dt used:

d[live shoot mass] = [1/(1 + rt/sht) * net production - litterfall rate * live shoot mass] * dt

d[dead shoots left] = [litterfall rate * live shoot mass * dt - % harvest * dead shoot mass]

d[dead shoot mass] = dead shoots left - [shoot decay rate * dead shoots left * dt]

d[live root mass] = [rt/sht/(1 + rt/sht) * net production - live root mass * root death rate] * dt

d[dead root mass] = [root death rate * live root mass - root decay rate * dead root mass] * dt

The first three equations above were used to determine the dead shoot mass. This value, along with the dead root mass, is included in the BOD removal kinetics model as a source of organic carbon. The live root mass is used to calculate the organic carbon compound assimilation on the roots. Numerical integration of the five plant quantities above is facilitated by the Runge Kutta method.

Section 3.4: BOD Removal Kinetics Submodel

From a carbon balance within the liquid portion of a rock-plant filter, the effluent BOD_5 concentration can be calculated. This balance is as follows:

d[C mass] = [C_{in} + C from plant decay - C assimilated by microorganisms - C removed by settling - C_{out}] * dt (9)

where terms in the parentheses to the right are in units of mg/day. These terms are further defined below:

C_{in} = C concentration in * influent flow

C from plant decay = mg C/grams plant dry weight * (dead shoot mass * shoot decay rate + dead root mass * root decay rate)

C assimilated by microbes = (K_{rock} * rock microbe mass + K_{root} * root microbe mass) * mass of C in system (where K_{rock} and K_{root} are temperature dependent rate constants)

C removed by settling = mass of C in system * C settling rate

C_{out} = mass of C in system/ system water volume * flow out

In the above equation for microbial assimilation of carbon, it is assumed that this reaction is dependent on the microbial population on the rock and root surfaces in addition to the mass of organic carbon present. Rock and root microbe masses were calculated assuming 10^5 microbes/cm^2 and an average microbe mass of 10^{-9} mg/microbe, taken from Jorgensen (1976). Since these populations are considered to be of constant density on the respective surfaces, the actual dependence the above assimilation rate equation incorporates is with the surface areas. As found in upflow filters where the media is suspended by upflow velocity, smaller rocks which have a larger available surface area per unit volume than larger rocks support a higher degree of microbial activity; likewise, a system with a high plant density would attain a larger microbial root population, and thus a higher assimilation rate, than a system with a lower plant density. Therefore, this modification to a first-order reaction is meant to incorporate differences between systems through an adjustment of the rate constant rather than a reordering of this reaction.

As in the plant submodel, the Runge Kutta method of integration was used to calculate the mass of carbon in the system over time. Values for the constants in the above equations were taken from the literature, where possible. The remaining values obtainable through the bench-scale study data were calibrated by systematically changing the parameter values until the sum of the squared residuals (SSR) was minimized. All constant values are listed in Table 2.1 along with the source from which they

TABLE 2.1: Values of Model Parameters and Their Sources

Parameter	Source	System*: 1	2	3	4
Initial live shoot mass	C	475g	2800g	0	40000g
rt/sht ratio	K&H	1	1	N/A	1
Initial dead root mass	C	2000g	2000g	0	400g
litterfall rate	K&H	0.2/dy	0.2/dy	N/A	0.2/dy
shoot decay rate	K&H	0.004/dy	0.004/dy	N/A	0.004/dy
root death rate	C	1E-5/dy	1E-5/dy	N/A	1E-5/dy
root decay rate	K&H	0.004/dy	0.004/dy	N/A	0.004/dy
root density	C	0.7g/cc	0.7g/cc	N/A	0.7g/cc
root area/ volume	C	8/cm	8/cm	N/A	8/cm
carbon per plant	MHB	429mg/g	429mg/g	N/A	429mg/g
Initial carbon concentration	C	30mg/l	20mg/l	100mg/l	15mg/l
K_{rock} at 20°C	C	0.02/mg /day	0.03/mg /day	0.01/mg /day	1E-7/mg /day
K_{root} at 20°C	C	0.2/mg /day	0.2/mg /day	N/A	0.1/mg /day
carbon settling fraction	C	0.5	0.5	0.3	0.5

Source abbreviations legend:

C : calibrated by minimizing SSR

K&H : Kadlec and Hammer (1988)

MHB : Morris, et al. (1984)

* - System numbers refer: 1 - Sagittaria bench-scale system, 2 - Scirpus bench-scale system, 3 - control bench-scale system, and 4 - Denham Springs full-scale system

were derived. The extremely low value for K_{rock} shown in this table for the Denham Springs system is probably due to a combination between very low plant density and low BOD loading to the filter, as compared to the bench-scale systems. Sensitivity to rock size and porosity were tested in the model using data from the Scirpus system and the Denham Springs system. For both systems, the SSR did not vary for changes in rock size from 1/4" to 9", nor for porosities ranging from 0.3 to 0.7.

Section 3.5: Finite Section Modification

To simulate plug flow within a full-scale rock-plant filter, the model presented above was modified by segmenting the filter into constant length sections. Effluent flows from each segment were calculated by summing the system inflow for first segment, or the outflow from the previous segment for all other segments, and precipitation and evapotranspiration on the segment area. Plant growth was considered to be uniform across the filter.

After performing hydraulic and plant calculations for each segment, a carbon mass balance for each finite section was calculated as described for the hydrologic balance above using the effluent carbon mass and flow rate from the previous section as the influent quantities to the subsequent section. The timestep used in this procedure was equal to the theoretical retention time for one section; therefore, as the section length decreased, so did the timestep. This timestep adjustment allowed the progression of contaminants through the filter to be considered each time they theoretically passed through a section. A constant timestep used in this model did not yield results which were as accurate as the variable timestep. In the computer model, the finite section length was decreased by increasing the divisions of total length until the SSR was a minimum. For the Denham Springs system, this optimum finite length was 500 feet, or one-half of the total length. If the model accurately represented every BOD_5 removal mechanism (i.e., there was no error in the model), an infinite number of sections would give the most accurate result, assuming plug flow. Each time the section length is reduced, however, the timestep is reduced and the number of calculations per month are increased. This tends to amplify error within the model. These errors include non-uniform plant and microbial growth within the filter, uneven distribution of wastewater across the width, and inability of the model to fully compensate for start-up conditions which were present in the Denham Springs system during the time period used. In addition, flow within a rock-plant filter is likely to be represented by a combination of plug flow and completely mixed conditions due to possible short-circuiting created through localized plugging by non-uniform sedimentation and bacterial growth plus pathways opened by plant root movements. For these reasons, the number of sections which produced the most accurate results was much less than infinity.

Chapter 4
SIMULATION RESULTS AND DISCUSSION

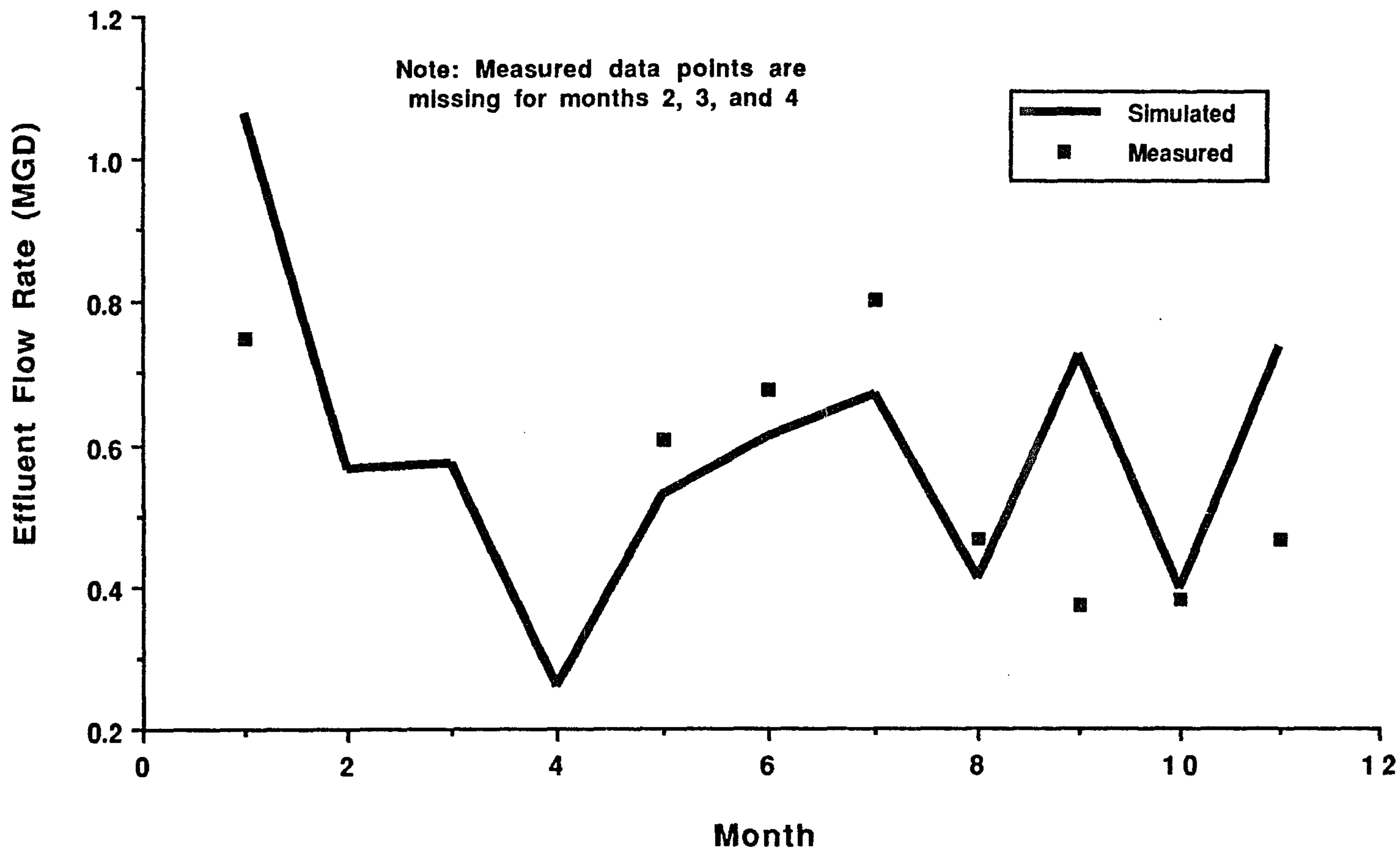
The simulations of the model developed above were conducted using the computer programs given in Appendix B. Also given in Appendix B is the data used in the Denham Springs rock-plant filter simulation. These two Appendix B computer programs are essentially the same except for the following differences in the Denham Springs simulation:

* finite section modifications discussed above;
* incorporation of precipitation and evapotranspiration quantities;
* differences in a few parameter values such as initial plant biomass, initial system carbon mass, and percent harvest.

Measured and simulated values from the simulations are comparable graphically and statistically, the latter through SSR values. Appendix C contains a listing of all simulated and measured values for the three bench-scale systems and the Denham Springs system. Simulated values are listed for the computer program of Appendix B and for equations (2) and (4) in the literature review section above.

Assessment of the hydrologic submodel is found by plotting measured and simulated flows for the Denham Springs system, as shown in Figure 2.3. The higher simulated values on months 1, 9, and 11 are probably due

Figure 2.3: Measured and Simulated Flow Rates - Denham Springs Rock-Plant Filter



to ponding which occurred on the actual filter. In the simulation, the east cell was used because ponding was less in it as compared to the adjacent two cells at this installation. Of all of the rock-plant filter systems in the United States accompanied by sufficient influent and effluent monitoring data, none are free of ponding, according to Sherwood Reed (a consultant for the EPA who is making a survey of constructed wetlands including collecting data bases). For the most part, this is because systems are not being designed using the Darcy equation and hydraulic conductivities suggested above in the literature review. Assuming proper design procedures will predominate in the future, provision for ponding was not included in the model.

Comparisons of measured and simulated live shoot mass quantities for the Part One bench-scale Sagittaria and Scirpus systems are graphically illustrated in Figures 2.4 and 2.5. Differences between simulated and measured values for the Sagittaria system are due to the die-off experienced at the beginning of this study when the system water level dropped during cleaning of the influent reservoir. Also, Sagittaria and Spartina are quite different species, unlike the similarity between Scirpus and Spartina. Figure 2.5 shows a good correlation between simulated and measured live shoot mass for the Scirpus system. The initial lag in measured mass at Day 10 is

Figure 2.4: Measured and Simulated Live Shoot Mas: Sagittaria System

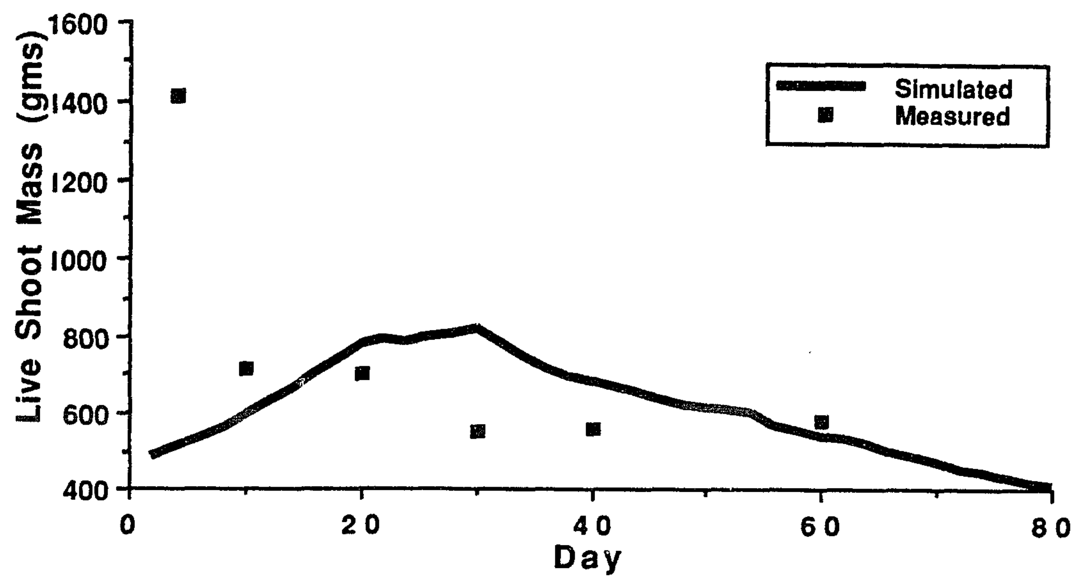
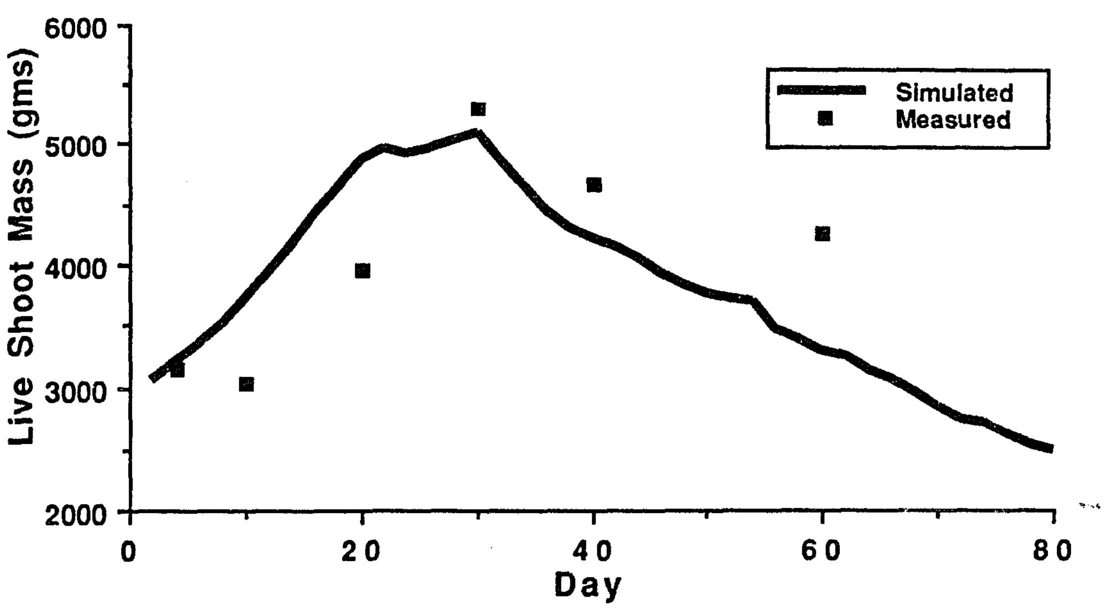


Figure 2.5: Measured and Simulated Live Shoot Mas: Scirpus System



probably due to the water level drop mentioned above. A more rapid drop off after Day 30 for the simulated mass could be due to the differences in environmental conditions between outdoors and the greenhouse.

Figures 2.6, 2.7, and 2.8 compare the measured and predicted effluent BOD_5 concentrations. Predictions in these graphs are by three methods:

(1) the computer simulation listed in Appendix B (Comp. Model)

(2) equation (2) above which is endorsed by the EPA, Water Pollution Control Federation, and the Tennessee Valley Authority (EPA Model)

(3) equation (4) above which is used largely in Europe (Eur. Model)

For the EPA simulations, the value of the temperature-dependent reaction constant was adjusted for each system until SSR reached a minimum. To compare SSR from simulations using different numbers of observations, the parameter SSR/obs, or SSR divided by the number of observations, was devised. These values for each prediction method are listed on the legend of each graph. SSR/obs values are consistently better for the computer model than the other two models.

To analyze the carbon mass balance used in predicting effluent BOD_5 concentrations, the four sources and sinks plus the influent and effluent carbon masses were plotted

Figure 2.6: Measured and Simulated Effluent BOD5 Concentratons - Sagittaria System

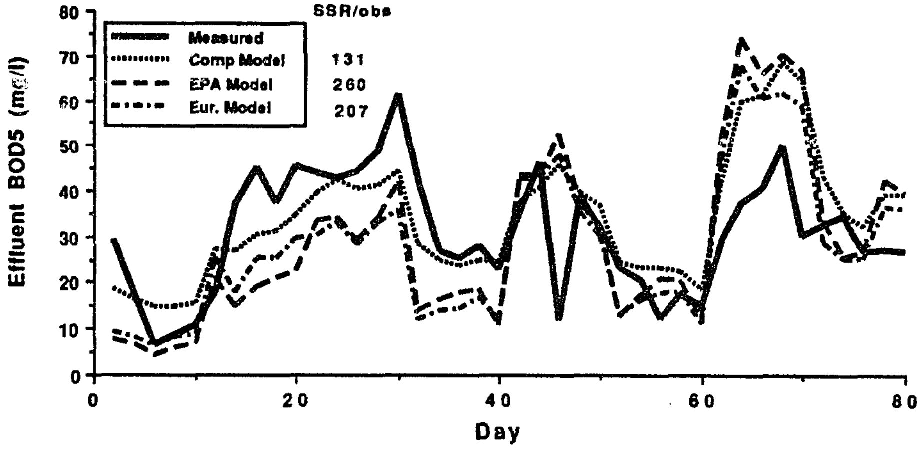


Figure 2.7: Measured and Simulated Effluent BOD5 Concentrations - Scirpus System

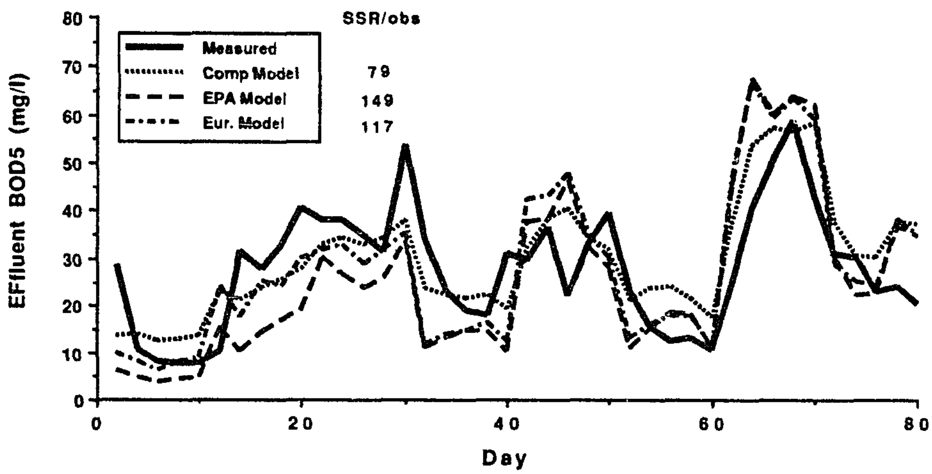
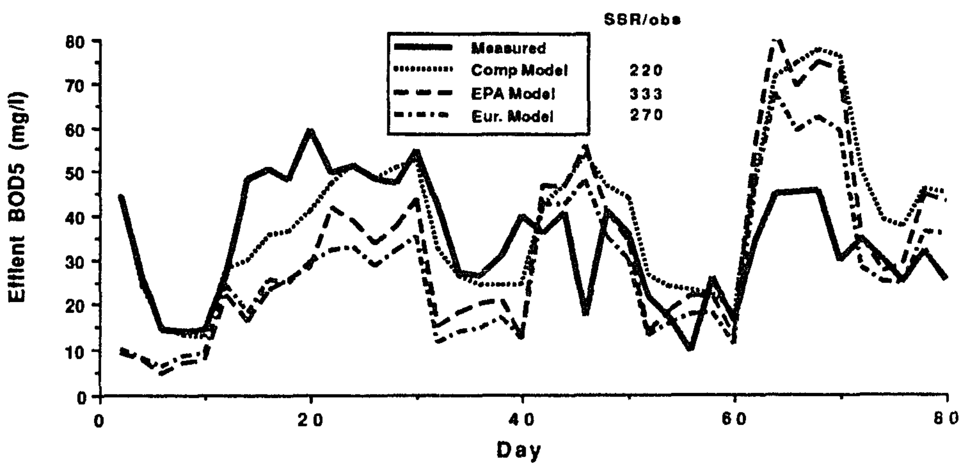


Figure 2.8: Measured and Simulated Effluent BOD5 Concentrations - Control System



for each of the bench-scale systems, as shown in Figures 2.9, 2.10, and 2.11. Carbon due to plant decay was relatively constant in the vegetated systems, although understandably higher for Scirpus than the Sagittaria since total aboveground biomass was much less for the latter. The sink described as settled carbon mass was virtually equivalent for both vegetated systems and only slightly reduced in the control during the two periods of highest flow and influent carbon levels. The loss reaction representing microbial assimilation on the rock surfaces was consistently the highest removal mechanism in all three systems, although in the control system this sink was almost aligned with the portion removed by settling. Between the two vegetated system, the carbon assimilated on the rock surfaces was always greater in the Scirpus system. This is interesting since the same amount of rock surface was available in both systems. A reason for this could be greater stimulation of aerobic degradation on rock surfaces adjacent to oxygen-producing roots which were more densely distributed throughout the Scirpus system. By contrast, the carbon sink assigned to assimilation on the root surfaces was consistently lower than the other removal mechanisms for both vegetated systems. In the Sagittaria system, this quantity was considerably lower than the other removal forms; whereas, in the Scirpus system, root assimilation was higher than

Figure 2.9: Division of Carbon Sources and Sinks - Sagittaria System

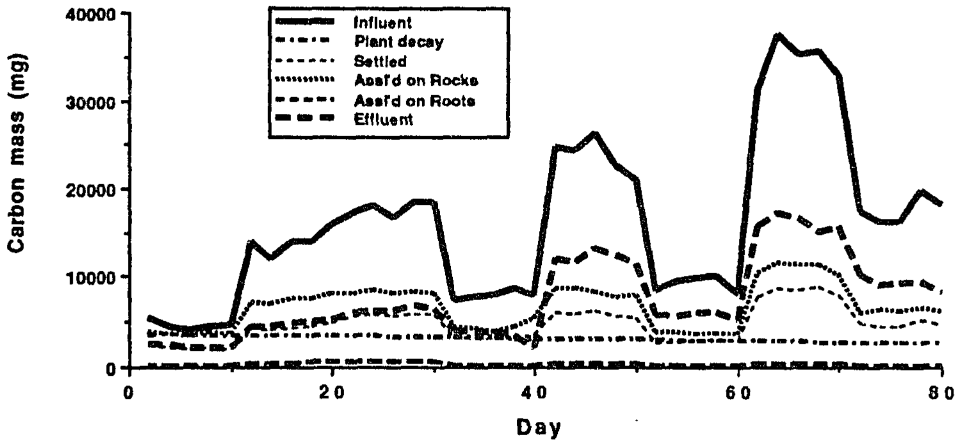


Figure 2.10: Division of Carbon Sources and Sinks- Scirpus System

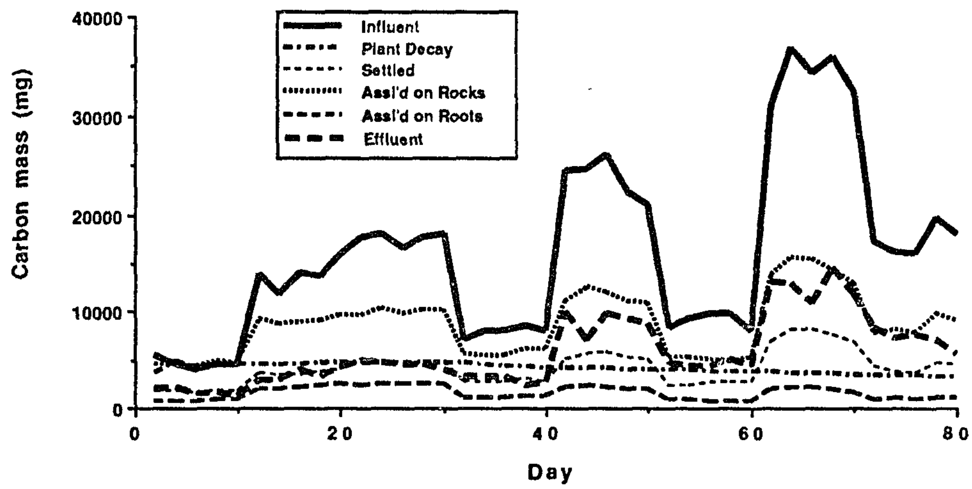
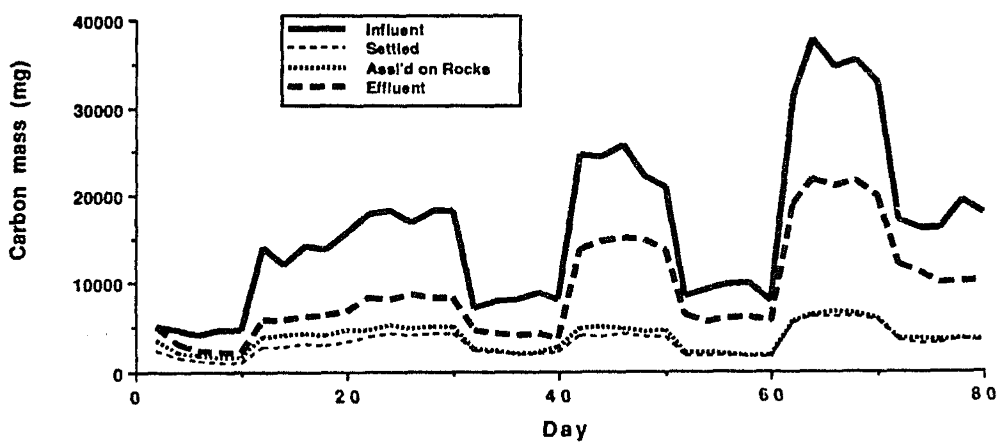


Figure 2.11: Division of Carbon Sources and Sinks - Control System



in the Sagittaria system, but roughly half of the portion assigned to removal by settling. According to this analysis, most of the BOD removal occurs on the rock surface, however, this mechanism is enhanced by a thick, active root mass.

Based on simplifications which can be drawn from the above observations, the carbon mass balance equation (9) above can be integrated and rearranged to become:

$$C_e = X/Y * (1 - e^{-Yt}) + C_o e^{-Yt}$$
(10)

Where

C_e = effluent BOD_5 concentration, mg/l

C_o = influent BOD_5 concentration, mg/l

t = retention time, days

$= (2 * V)/(Q_o + Q_e)$

$X = C_o * Q_o + 4.7E-3 * A$

$Y = Q_e + (393 * A * K * V)$

V = volume of water in filter, liters

Q_o, Q_e = influent and effluent flow rate, liters/day

A = filter surface area, meters^2

$K = 1E-7 * (1.047)^{T-20}$ /mg microbes/day

T = water temperature, °C

This simplification of the computer model assumes a constant BOD_5 contribution from decaying plant matter of 4.7 g/day/m^2 and a live root mass of 720 grams/m^2. These values are high for decaying plant matter and low for live root mass; this will give a lower reduction of BOD than may actually occur and is thus conservative. Derivation of equation (10) is given in Appendix D.

A further simplification can be made to equation (10) by realizing that, even for the bench-scale systems which had a low flow rate and a relatively short detention time, Yt is a very large number. Thus, equation (10) reduces to:

$$C_e = X/Y \qquad (11)$$

Furthermore, for the Denham Springs east cell, using one finite section and equation (11) resulted in the lowest SSR/oberservation value, or best fit, as compared to using 2, 4, and 6 sections. Predicted effluent BOD_5 concentrations from the European and EPA equations, along with those from the computer model and equation (11) are plotted with the measured values in Figure 2.12. Visual observation and SSR/observation values for each simulation indicate the computer model and equation (11) predicted actual concentrations more accurately than the other two models. It should be noted that, since these simulations are based on different assumptions, performance of the model is directly linked to the realism of these assumptions.

To further analyze the results depicted in Figure 2.12, a time series plot of the residuals from each simulation is shown in Figure 2.13. As noted in this

Figure 2.12: Measured and Simulated Effluent BOD5 Concentrations - Denham Springs RPF

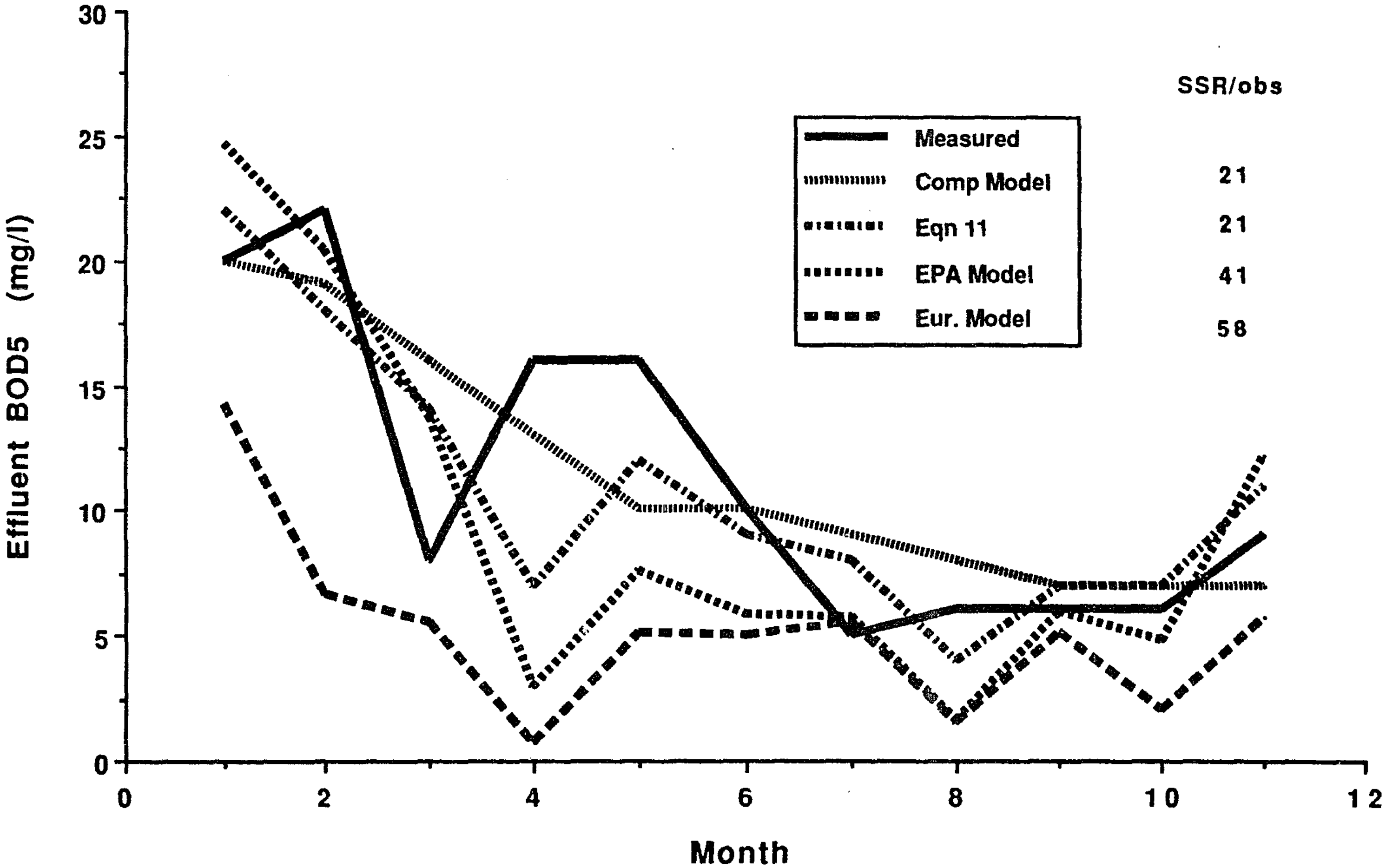
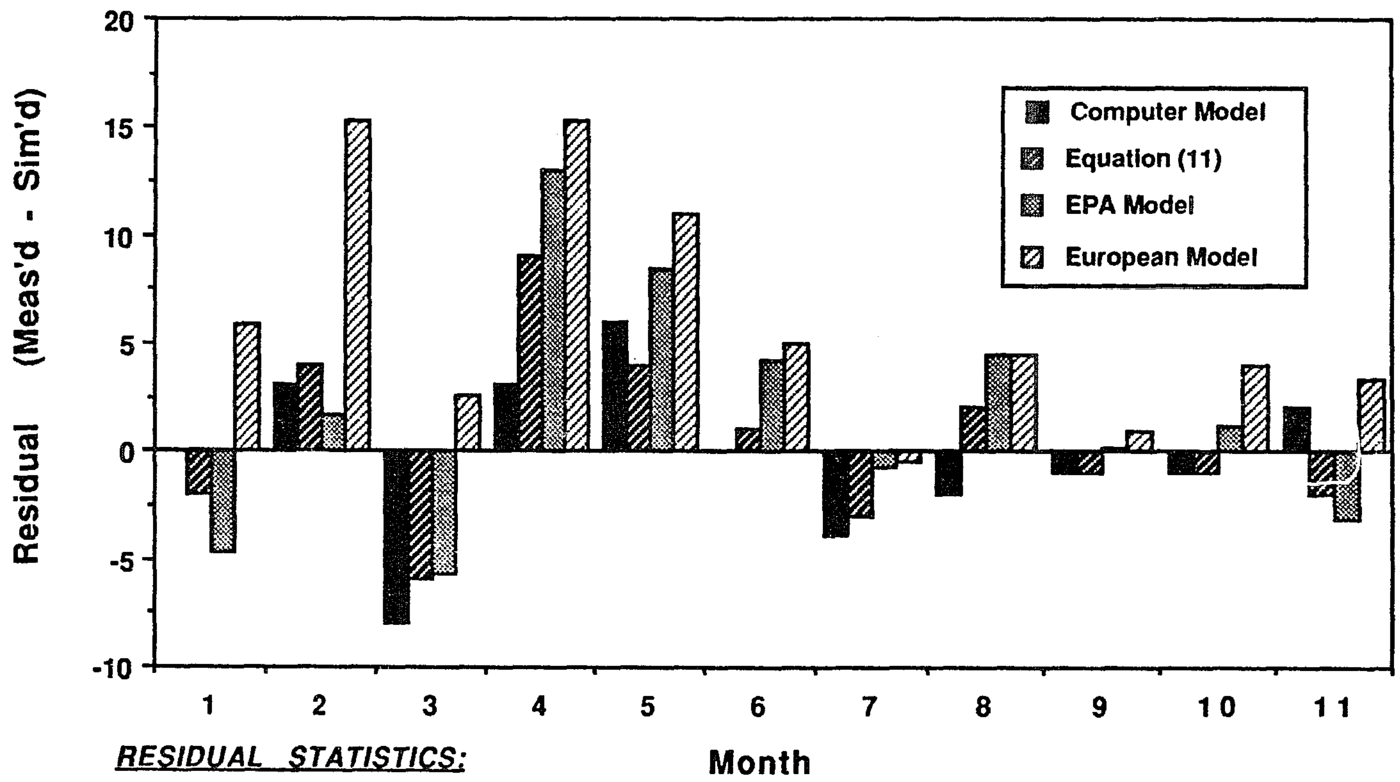


Figure 2.13: BOD5 Residuals for Each Model



RESIDUAL STATISTICS:

	Comp Model	Eqn (11)	EPA Model	Eur. Model
Mean	-0.2	0.5	1.5	5.9
Variance	13.1	15.5	28.6	26.8

figure, the residual average was lowest for the computer model followed closely by equation (11). In addition, the variances of both the computer model and equation (11) residual values are approximately half the residual variances from the EPA and European models. These statistics indicate that, not only is the overall accuracy increased by using the computer model, but the frequency of accurate observations is also increased.

Design of a rock-plant filter using the computer model or equation (11) should begin by first determining the required width according to the Darcy equation, assuming a hydraulic conductivity of around 10^{-4}m/s. Then, the length required to attain a specified effluent concentration can be calculated by trial and error using the computer model or the above equation (11).

Chapter 5
CONCLUSIONS

Conclusions derived from this study include:

1) The primary removal advantage of horizontal flow, flooded rock-plant filters is in BOD5 removal. Solids may eventually create clogging and nitrification, as the limitation in nitrogen removal, has been observed to be poor in this and other studies.

2) If nitrification is performed prior to the rock-plant filter system, however, denitrification is readily performed in the rock-plant filter environment (assuming an adequate carbon supply is available).

3) Very low or anoxic conditions prevailed in the bench-scale systems.

4) According to the computer model developed herein, the degradation occurring in the biofilm on the rock surface is the most significant carbon sink; however, the presence of plants appears to significantly enhance this degradation.

5) By considering the water budget, plant growth factors, and removal of carbon by settling, in addition to microbial degradation, the model developed herein was significantly more accurate in predicting the effluent BOD5 concentration of all

three bench-scale systems and the Denham Springs system as compared to the other two currently-used equations.

6) By making a few simplifications based on an analysis of the computer model sinks and sources, an equation was derived which uses common parameters. This simplified equation had an accuracy approximately equal to the computer model.

Chapter 6
RECOMMENDATIONS

Although the computer model and the simplified equation (11) predicted effluent BOD_5 concentrations more accurately in the cases considered herein, this accuracy may be increased by research in the following areas:

a) change in hydraulic conductivity over time as a function of suspended solids and sludge buildup plus plant growth.

b) plant growth of Scirpus and Phragmites species as a function of climatic factors, similar to the Spartina equations developed by J.T. Morris and used in the model development herein.

c) evapotranspiration within small, constructed wetlands.

Comparably, little more can be done to improve equations (2) and (4), except to adjust the first-order reaction constant. In addition, it appears clear from this and other studies that the aquatic plants are enhancing the treatment of BOD_5- producing compounds. Thus, a model which considers the variability of this component would logically be more representative of the actual system.

The reason for BOD_5 treatment enhancement due to plants is related to radial oxygen loss through the plant roots (discussed in Section 2.3) more than any other factor. For example, removal of BOD_5- producing, or organic carbon, compounds through plant uptake is not accounted for in carbon cycles, as described by Jorgensen (1979) and Logofet and Alexandrov (1988). Similarly, removal of nitrogen through plant uptake does not appear to be a major removal mechanism as plant harvesting produces little improvement in nitrogen removal, as noted by Spangler, et al. (1976) and Wieder, et al. (1989).

The connection between enhanced degradation of organic carbon compounds and radial oxygen loss is evidenced by the presence of strict aerobic bacteria found on Phragmites (reed) roots growing in sludge or wastewater by May, et al. (1990) and Hofmann (1990). Increased dissolved oxygen concentration due to plants, however, is not adequate for significant nitrogen removal because of low nitrification rates. Since nitrogen removal is an increasing concern, research aimed at determining the kinetics of root oxygen loss under various loading conditions in a rock-plant filter, as well as methods of increasing or assisting the elevated dissolved oxygen concentration produced by aquatic plant roots is recommended as the most important direction toward upgrading the rock-plant filter system.

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APPENDIX A

Data from Bench-Scale Study

ROCK-PLANT FILTER BENCH-SCALE STUDY
LOG OF SIGNIFICANT EVENTS

11/17/88 Flow in the three rock filters began with recycle mode

11/19/88 Ten plants/tank planted in tanks #1 (Sagittaria) and #2 (Bulrush). Hydrosol (a hydroponic fertilizer) + CaNO3 used to supplement feed-water.

1/4/89 Sprayed Sagittaria with Malathion for aphids.

1/9/89 Sprayed Sagittaria again with Malathion for aphids.

1/17/89 Seeded recycling water with 2 liters of mixed liquor from Brightside activated-sludge plant and added dextrose periodically thereafter.

[Feed tank cleaned and refilled once every week or two. Pump cleaned at this time also]

2/15/89 Reseeded tanks directly with activated-sludge mixed liquor.

2/18/89 Most of Scirpus (bulrush) stalks cut to grade due to red mite attack; then periodically sprayed with biologically safe spray to ward off future attacks of mites. Also misted twice/day to cut down mites. Scirpus stalks grew back rapidly.

4/12/89 Changed system to flow-through from common feed reservoir. Flow-rate adjusted to 70 ml/min (about 2 day detention time).

4/27/89 Final (#6) synthetic wastewater containing glucose settled on.

5/9/89 BOD low (3 to 6 mg/l). Spiked with 10x the amount of glucose.

5/19/89 Flow adjusted to 80 ml/min (about 1.8 day detention time).

6/4/89 Pump #3out.

6/6/89 Temporary, continuous flow pump #3 installed (pumps 1 and 2 have a pulsating flow)

6/7/89 Changed organic substrate from glucose + NH4SO4 to Difco nutrient broth (about 40 mg/l BOD, 10 mg/l TKN).

6/17/89 Pre-aeration of feed-water began.

7/20/89 Increased BOD level in feed tank to about 150 mg/l.

7/22/89 Original pump #3 reinstalled.

8/13/89 Flow adjusted four times/day; pH in feed adjusted to 7 to 7.5.

8/15/89 Cleaned feed tank and let it sit in tap water for 24 hours. (Water level in tanks 1 & 2 dropped quite a bit.)

8/16/89 Began autoclaving BOD bottles.

8/22/89 Decreased BOD to about 150 mg/l (87 g nutrient broth). Started using distilled water in BOD analysis (as opposed to deionized)

8/24/89 Reservoir sampling changed to a composite of old + new.

8/26/89 Decreased BOD to around 50 mg/l.

10/28/89 Feed tank ran dry probably in the evening.

Data from Preliminary Investigation

ROCK-REED FILTER DATA

FEED RESERVOIR

	AIR TEMP (oC)			COD(mg/l)		BOD(mg/l)		COD	TKN (mg/l)		NH4 (mg/l)	
DATE	low	high	pH	mean	std dev	mean	std dev	/BOD5	mean	std dev	mean	std dev
12-Apr-89	64	100										
18-Apr-89	63	101										
20-Apr-89	70	100				6.6	0.2				12.4	0.2
26-Apr-89	72	104										
27-Apr-89	72	106				3.0	0.1					
29-Apr-89	72	102	8									
01-May-89	72	104	8									
02-May-89	70	102										
03-May-89												
04-May-89	72	86										
05-May-89			8									
06-May-89	74	96										
07-May-89	70	101										
08-May-89			8									
09-May-89	70	104										
10-May-89	76	100										
11-May-89	67	93										
12-May-89											4.5	1.2
13-May-89	67	93	7.7	60.0	1.4							
14-May-89	73	92		68.0	7.0							
15-May-89	73	105	7.8	80.0	2.0							
16-May-89	73	102	7.7	69.0	0.0							
17-May-89	77	103	7.7	62.5	1.5							
18-May-89	78	98	7.9	74.0	2.0							
19-May-89	73	94	7.9	79.0	3.0							
20-May-89	77	112	7.8	63.7	2.9							
21-May-89	75	110	8.2	64.5	1.5							
22-May-89	75	115	8.2	65.0	1.4							
23-May-89	80	100	8.2	75.0	1.4	7.4	0.0	10.18			8.8	0.3
24-May-89	80	118	8.3	74.7	7.4						9.0	0.7
25-May-89	80	117		56.0	0.0							
26-May-89	84	110		28.3	6.3							
27-May-89	80	105	7.6	193.0	4.5							
28-May-89	78	110	6.9	146.7	1.9							
29-May-89	78	103	6.8	128.0	3.3						5.5	0.0
30-May-89	78	106		188.0	1.4							
31-May-89			7.4	83.0	5.9	2.1	0.2	38.91				
01-Jun-89			6.6	158.0	1.4							
02-Jun-89			7.6	149.0	11.3							
03-Jun-89			6.8	137.0	2.4							
04-Jun-89			7.8	208.0	4.2							
05-Jun-89			7.7								10.5	0.0

DATE	AIR TEMP (oC) low	high	pH	COD(mg/l) mean	std dev	BOD(mg/l) mean	std dev	COD /BOD5	TKN(mg/l) mean	std dev	NH4 (mg/l) mean	std dev
06-Jun-89	74	90	7.4									
07-Jun-89	75	100	7.3									
08-Jun-89	77	94	7.7	60.0	1.4							
09-Jun-89	75	101	8	62.3	9.0							
10-Jun-89	78	96	7.8	126.7	47.2							
11-Jun-89	78	98	7.8	66.0	4.5							
12-Jun-89	80	102	7.7	47.0	8.5							
13-Jun-89	80	92	7.5	58.7	5.2							
14-Jun-89	81	100	7.6	61.7	1.2	40.3	19.2	1.53				
15-Jun-89	77	92	7.6	63.3	10.5							
16-Jun-89	74	94	8	67.7	0.9				10.4	0.1	7.6	0.1
17-Jun-89	74	92		61.0	2.9							
18-Jun-89	64	96										
19-Jun-89	64	96	7.5									
20-Jun-89	62	98	7.5									
21-Jun-89	72	98	7.3			29.0	1.8					
22-Jun-89	68	94	7.2									
23-Jun-89	60	90	7.3			29.5	0.7					
24-Jun-89	60	94										
25-Jun-89	60	98										
26-Jun-89	98	77	7.5									
27-Jun-89	79	91	7.4									
28-Jun-89												
29-Jun-89	99	77	7.4									
30-Jun-89	79	103	7.3									
01-Jul-89	79	86										
02-Jul-89	80	100										
03-Jul-89	77	102	7.3	48.6	1.6							
04-Jul-89	76	94	7.3									
05-Jul-89	76	89	7.4	68.6	1.6	35.7	2.1	1.92				
06-Jul-89	77	92	7.4									
07-Jul-89	76	101	7.8	72.4	6.9	21.5	2.0	3.37				
08-Jul-89	77	96										
09-Jul-89	78	100										
10-Jul-89	78	110	7.6	51.0	1.6						4.2	0.1
11-Jul-89	77	97	7.3						5.1	0.1		
12-Jul-89	78	105	7.4	43.4	2.7	27.1	2.3	1.60				
13-Jul-89	79	100	7.4									
14-Jul-89	78	100		44.9	1.6				10.4	0.1		
15-Jul-89	78	100										
16-Jul-89	78	101										
17-Jul-89	78	100		54.2	1.6						4.5	0.01
18-Jul-89	78	103							10.6	0.1		
19-Jul-89	78	104	7.6	43.8	1.7	45.7	1.1	0.96				

	AIR TEMP (oC)			COD (mg/l)		BOD (mg/l)		COD/	TKN (mg/l)		NH4 (mg/l)	
DATE	low	high	pH	mean	std dev	mean	std dev	BOD5	mean	std dev	mean	std dev
20-Jul-89	74	104	8.3									
21-Jul-89	77	94	7.3	322.3	1.9				10.8	0.2		
22-Jul-89	78	91										
23-Jul-89	77	90										
24-Jul-89	75	90	7.3	216.8	1.8						4.0	0.02
25-Jul-89	78	94							10.5	0.1		
26-Jul-89	76	88	7.3									
27-Jul-89	80	102	7.4	225.2	3.4							
28-Jul-89	80	102	7.3	290.7	1.6				26.0	3.5		
29-Jul-89	79	98										
30-Jul-89	78	98										
31-Jul-89	78	100	7.3	234.6	1.6						9.7	0.07
01-Aug-89	80	92	7.5									
02-Aug-89	80	93	7	295.4	3.3							
03-Aug-89	79	96				18.4	5.0					
04-Aug-89	80	98	7.6	313.9	4.3	16.4	2.9	19.12				
05-Aug-89	77	98										
06-Aug-89	78	100										
07-Aug-89	80	97	7.6	269.0	5.7						7.1	0.05
08-Aug-89	76	96	7.4									
09-Aug-89	72	90	7.8	279.6	1.6							
10-Aug-89	74	94	7.9									
11-Aug-89	74	93	7.8	273.3	1.6							
12-Aug-89	74	94										
13-Aug-89	78		7.2									
14-Aug-89	76	94	7.3									
15-Aug-89	76	90	7.5									
16-Aug-89	76	94	7.3									
17-Aug-89	76	95	7.4									
18-Aug-89	78	90	7.4									
19-Aug-89	76	90	7.4									
20-Aug-89	79	92	7.4									
21-Aug-89	79	99	7.4									
22-Aug-89	79	90	7.3	260.0	1.6	133.0	5.7	1.95				
23-Aug-89	78	94	7.3									
24-Aug-89	80	90	7.4	182.7	6.8							
25-Aug-89	79	94	7.5									

ROCK-REED FILTER DATA

FEED RESERVOIR

TS(mg/l)		TVS (mg/l)		TSS (mg/l)		TVSS (mg/l)		
mean	std dev	mean	std dev	mean	std dev	mean	std dev	DATE
								12-Apr-89
								18-Apr-89
483.3	38.6	106.7	33.0	40.0	14.4	6.7	5.3	20-Apr-89
								26-Apr-89
								27-Apr-89
545.0	15.0	25.0	15.0	56.5	16.5	33.0	0.0	29-Apr-89
416.7	171.3	23.3	17.0					01-May-89
								02-May-89
								03-May-89
526.7	26.2	46.7	12.5	13.5	6.5	7.0	0.0	04-May-89
								05-May-89
								06-May-89
								07-May-89
								08-May-89
								09-May-89
								10-May-89
								11-May-89
								12-May-89
								13-May-89
								14-May-89
								15-May-89
								16-May-89
								17-May-89
								18-May-89
								19-May-89
								20-May-89
								21-May-89
								22-May-89
								23-May-89
								24-May-89
636.7	30.9	440	28.3	30.0	10.8			25-May-89
								26-May-89
								27-May-89
								28-May-89
								29-May-89
610.0	17.8			13.3	6.2			30-May-89
								31-May-89
605.3	8.2	142.7	6.8	38.3	8.5			01-Jun-89
								02-Jun-89
								03-Jun-89
								04-Jun-89
								05-Jun-89

TS(mg/l) mean	TS(mg/l) std dev	TVS(mg/l) mean	TVS(mg/l) std dev	TSS(mg/l) mean	TSS(mg/l) std dev	TVSS(mg/l) mean	TVSS(mg/l) std dev	
553.3	13.1	160.0	10.8	32.3	5.2	9.0	4.3	06-Jun-89
								07-Jun-89
546.7	6.2	66.7	6.2	28.0	7.0	6.3	3.3	08-Jun-89
								09-Jun-89
								10-Jun-89
								11-Jun-89
								12-Jun-89
536.7	68.8	21.7	16.5	347.3	5.2	273.3	4.7	13-Jun-89
								14-Jun-89
535.0	67.5	21.7	2.5	350.7	4.0	279.7	2.5	15-Jun-89
								16-Jun-89
								17-Jun-89
								18-Jun-89
								19-Jun-89
530.0	28.3	90.0	4.1	23.3	9.4	21.7	3.1	20-Jun-89
								21-Jun-89
								22-Jun-89
560.0	46.4	96.7	17.0					23-Jun-89
								24-Jun-89
								25-Jun-89
								26-Jun-89
475.0	38.9	90.0	35.6	15.8	4.2	5.8	1.2	27-Jun-89
								28-Jun-89
440.0	145.1	68.3	8.5	10.0	2.0	6.7	2.4	29-Jun-89
								30-Jun-89
								01-Jul-89
								02-Jul-89
								03-Jul-89
553.3	12.5	161.7	13.1	50.7	0.9	19.7	5.6	04-Jul-89
								05-Jul-89
561.7	26.6	76.7	2.4	14.2	3.1	10.0	2.0	06-Jul-89
								07-Jul-89
								08-Jul-89
								09-Jul-89
								10-Jul-89
730.0	207.6	75.0	24.8	6.7	1.2	4.2	1.2	11-Jul-89
								12-Jul-89
								13-Jul-89
								14-Jul-89
								15-Jul-89
								16-Jul-89
								17-Jul-89
								18-Jul-89
								19-Jul-89

ROCK-REED FILTER DATA

SYSTEM ONE (SAGITTARIA OR ARROWROOT)

DATE	FLOWS (ml/min) IN	OUT	pH	WATER TEMP (o	ORP (mV) A	B	COD (mg/l) mean	std dev	%COD REM'D	BOD5 mean	std dev	COD /BOD5
12-Apr-89				22	209	263						
18-Apr-89				32	392	272						
20-Apr-89				26						4.2	0.7	
26-Apr-89	68			25								
27-Apr-89				27	-267	-117				4.2	0.4	
29-Apr-89	72		7	26								
01-May-89	72		7	25	-266	-146						
02-May-89	77			27	-247	-147						
03-May-89	73	64	7.1	25	-196	-136						
04-May-89	73				-255	-136						
05-May-89	70		7.1	22	-254	-207						
06-May-89				24	-245	-85						
07-May-89				24	-205	-125						
08-May-89	60		7.1	25	-185	-126						
09-May-89	70	50			-247	-137						
10-May-89	63			26	-217	-136						
11-May-89	74	54		23	-215	-215						
12-May-89	74	62		23	-213	-213						
13-May-89	72		6.9	24	-225	-205	144.0	2.4				
14-May-89	70			26	-247	-217	80.3	4.7				
15-May-89	75		7	27	-237	-227	68.5	3.5				
16-May-89	66	57	7.3	26	-237	-236	57.0	5.0	28.7			
17-May-89	77	70	7.1	26	-257	-147	35.5	1.5	48.4			
18-May-89	72	38	7.3	27	-187	-197	42.0	7.0	70.0			
19-May-89	73	67	7.3	25	-226	-196	30.5	1.5	64.6			
20-May-89	79	68	7.2	28	-228	-108	12.0	1.4	83.8			
21-May-89	76	76	7.3	27	-218	-108	15.0	0.0	76.7			
22-May-89	80	84	7.3	27	-187	-97	12.3	1.9	80.1			
23-May-89	86	86	7.2	27	-238	-108	21.3	4.7	71.6	3.4	0.2	6.3
24-May-89	56	48	7	28	-219	-119	25.0	1.4	71.3			
25-May-89	56	48		29	-219	-119	6.0	2.0	90.8			
26-May-89	76	72			-199	-119	7.0	1.4	76.6			
27-May-89			7.2	29	-249	-129	33.0	4.5				
28-May-89	92	78	7.2	30	-249	-149	19.0	0.0	89.0			
29-May-89	86	74	7.3	29	-259	-199	53.0	25.5	64.4			
30-May-89	74	70		29	-258	-208	69.3	30.9	65.1			
31-May-89	82	72	7.1	29	-249	-229	51.0	1.4	46.0	2.1	0.2	23.9
01-Jun-89	80	70	7.1				58.3	3.3	67.7			
02-Jun-89	76	76	7.1	26	-257	-226	15.5	8.5	89.6			
03-Jun-89	74	61	7.4	25.5	-236	-226	36.3	4.7	78.1			
04-Jun-89	77	62	7.2	26	-217	-217	54.3	2.9	79.0			
05-Jun-89	82	80	7.1	26	-247	-226						

DATE	FLOWS (ml/min) IN	OUT	pH	WATER TEMP (oC)	ORP (mV) A	B	COD (mg/l) mean	std dev	%COD REM'D	BOD5 mean	std dev	COD /BOD5
06-Jun-89	90	74	7.1	26	-257	-227						
07-Jun-89	92	76	7.1	25	-257	-227						
08-Jun-89	84	74	7.2	26	-247	-217	68.7	1.9	-0.8			
09-Jun-89	84	64	7.3	27	-247	-147	58.7	21.9				
10-Jun-89	82	74	7.2		-198	-138	23.3	6.0				
11-Jun-89	80	74	7.3	27	-217	-137	22.0	4.5				
12-Jun-89	82	72	7.3		-188	-128	27.0	4.5				
13-Jun-89	84	48	7.1	27	-217	-127	17.7	3.3				
14-Jun-89	86	70	7.1	27	-227	-137	23.0	0.0	69.6	7.4	1.5	3.1
15-Jun-89	76	68	7.2	26	-227	-137	25.0	1.4	64.7			
16-Jun-89	80	72	7.2	28	-228	-148	26.0	1.4	65.4			
17-Jun-89	88	74		28	-228	-148						
18-Jun-89	87	78		29	-218	-138						
19-Jun-89	86	76	7	28	-219	-139						
20-Jun-89	86	74	6.9	29.5	-218	-168						
21-Jun-89	86	72	6.8	28	-209	-139				5.4	0.7	
22-Jun-89	82	80	6.8		-198	-138						
23-Jun-89	84	74	6.9	28	-188	-138				5.9	0.1	
24-Jun-89	78	68		27	-197	-147						
25-Jun-89	84	70		28	-198	-138						
26-Jun-89	92	80	7.1	28	-208	-148						
27-Jun-89	78	68	7.1	28	-208	-148						
28-Jun-89												
29-Jun-89	78	66	6.9	29.5	-189	-159						
30-Jun-89	82	64	7	32	-181	-181				3.2	0.3	
01-Jul-89	78	66		29	-139	-179						
02-Jul-89	80	66		30	-199	-179						
03-Jul-89	78	66	6.8	28	-198	-198	24.1	22.4	58.0			
04-Jul-89	82	76	7	27.5	-238	-198						
05-Jul-89	84	76	7.1	27	-217	-197	23.2	1.6	69.4	7.0	2.8	3.3
06-Jul-89	82	72	7.1	28	-228	-198						
07-Jul-89	80	72	7.3	27.5	-218	-198	38.4	4.2	52.2	5.1	0.7	7.6
08-Jul-89	80	68		28.5	-218	-208						
09-Jul-89	78	70		30	-219	-209						
10-Jul-89	78	68	7.1	30	-239	-209	26.0	1.6	55.6			
11-Jul-89	84	78	6.8	29	-239	-209						
12-Jul-89	110	100	6.9	30	-239	-209	16.2	1.6	66.1	4.3	2.4	3.8
13-Jul-89	86	64	6.9	31	-240	-210						
14-Jul-89	100	86			-239	-209	17.3	1.6	67.0			
15-Jul-89	82	70			-238	-218						
16-Jul-89	82	68			-238	-208						
17-Jul-89	80	66			-239	-219	22.6	1.9	65.6			
18-Jul-89	80	62			-249	-229						
19-Jul-89	81	70	7.4		-259	-209	25.6	4.5	49.5	4.4	0.4	5.8

DATE	FLOW (ml/min) IN	OUT	pH	WATER TEMP(oC)	ORP (mV) A	B	COD (mg/l) mean	std dev	%COD REM'D	BOD5 (mg/l) mean	std dev	COD /BOD5
20-Jul-89	82	78	7	30	-259	-239			60.4			
21-Jul-89	80	67	7.2	28	-328	-258	31.3	3.3	91.9			
22-Jul-89	80	54		28	-328	-288						
23-Jul-89				27	-317	-287						
24-Jul-89	90	80	6.8	27	-307	-297	298.7	3.4	-22.5			
25-Jul-89	104	70		27.5	-308	-268						
26-Jul-89	74	60	7	27	-307	-277						
27-Jul-89	74	70	7.1	30	-319	-299	200.1	1.7	15.9			
28-Jul-89	84	70	7.3	30	-329	-309	205.0	3.3	41.2			
29-Jul-89	104	92		28.5	-318	-308						
30-Jul-89	80	66		29	-329	-309						
31-Jul-89	70	50	7.2	29	-319	-309	201.5	3.4	38.7			
01-Aug-89	80	62	7.2	28	-308	-318						
02-Aug-89	80	54	7.1	29	-309	-309	172.4	3.3	60.6			
03-Aug-89	80	74		28.5	-328	-308				74.8	16.3	
04-Aug-89	80	76	7.3	30	-329	-309	313.9	4.3	5.0	87.1	6.3	3.6
05-Aug-89	80	74		29.5	-329	-309						
06-Aug-89	80	71		30.5	-330	-320						
07-Aug-89	80	68	7.6	30.5	-330	-320	197.6	9.2	37.6			
08-Aug-89	82	74	7.4	27	-247	-307						
09-Aug-89	81	73	7.8	26.5	-317	-317	177.8	1.6	42.7			
10-Aug-89	87	70	7.9	26.5	-337	-317						
11-Aug-89	84	71	7.8	27	-247	-317	190.0	3.1	41.2			
12-Aug-89	84	79		27	-337	-327						
13-Aug-89	80	80		27	-337	-327						
14-Aug-89	82	61		28	-348	-328						
15-Aug-89	80	79		28	-348	-328						
16-Aug-89	79	66		27.5	-328	-328						
17-Aug-89	83	69		28	-348	-328						
18-Aug-89	79	64		28	-328	-328						
19-Aug-89	82	65		28	-328	-328						
20-Aug-89	82	65		28.5	-348	-328						
21-Aug-89	81	64		29	-329	-349						
22-Aug-89	82	77		29.5	-359	-339	167.8	3.1	39.4	183.0	3.0	0.9
23-Aug-89	80	51		29	-339	-339		AVG 102-135.61				
24-Aug-89	81	67		29	-349	-339	110.7	3.8	50.3	40.7	4.2	2.7
25-Aug-89	78	64		29	-349	-329						

ROCK REED FILTER DATA

SYSTEM ONE (SAGITTARIA OR ARROWROOT)

TKN mean	TKN std dev	NH4 mean	NH4 std dev	%NH4 REM'D	TS mean	TS std dev	TVS mean	TVS std dev	TSS mean	TSS std dev	TVSS mean	TVSS std dev	DATE
													12-Apr-89
													18-Apr-89
		1.4	0.1										20-Apr-89
					746.7	61.3	93.3	36.8	27.0				26-Apr-89
													27-Apr-89
					516.7	81.8	80.0		27.0	0.0	7.0	0.0	29-Apr-89
					586.7	47.1	30.0	29.4	4.0	2.9	5.0		01-May-89
													02-May-89
													03-May-89
					560.0	24.5	36.7	12.5	13.0				04-May-89
													05-May-89
													06-May-89
													07-May-89
													08-May-89
													09-May-89
													10-May-89
													11-May-89
													12-May-89
													13-May-89
													14-May-89
													15-May-89
													16-May-89
													17-May-89
													18-May-89
													19-May-89
													20-May-89
													21-May-89
													22-May-89
													23-May-89
		4.7	0.0	55.1									24-May-89
					603.3	17.0	426.7	34.0	48.3	6.2			25-May-89
													26-May-89
													27-May-89
													28-May-89
		4.1	0.0	35.7									29-May-89
					543.3	8.5			20.0	*			30-May-89
													31-May-89
					599.7	39.3	68.0	13.1	2.5	2.5			01-Jun-89
													02-Jun-89
													03-Jun-89
													04-Jun-89
		6.5	0.0										05-Jun-89

TKN mean	TKN std dev	NH4 mean	NH4 std dev	%NH4 REM'D	TS mean	TS std dev	TVS mean	TVS std dev	TSS mean	TSS std dev	TVSS mean	TVSS std dev	DATE
					558.3	6.2	103.3	2.4	32.0	4.1	7.3	2.1	06-Jun-89
													07-Jun-89
					561.7	22.5	45.0	7.1	14.7	3.8	4.7	2.1	08-Jun-89
													09-Jun-89
													10-Jun-89
													11-Jun-89
													12-Jun-89
					578.3	53.3	5.0	4.1	343.0	5.4	276.3	6.6	13-Jun-89
													14-Jun-89
					590.0	25.5	20.0	12.2	344.7	3.3	279.7	3.8	15-Jun-89
5.95	0	5.6	0.05	34.1									16-Jun-89
													17-Jun-89
													18-Jun-89
													19-Jun-89
					562.3	26.6	65.0	8.2	19.7	5.6	15.0	7.1	20-Jun-89
													21-Jun-89
													22-Jun-89
					613.3	30.6	76.7	17.0					23-Jun-89
													24-Jun-89
													25-Jun-89
													26-Jun-89
					616.7	32.7	128.3	31.7	11.3	3.3	6.3	3.3	27-Jun-89
													28-Jun-89
					640.0	35.6	53.3	10.3	12.5	2.0	6.7	1.2	29-Jun-89
													30-Jun-89
													01-Jul-89
													02-Jul-89
													03-Jul-89
					563.3	18.9	116.7	10.3	21.3	10.5	12.3	5.6	04-Jul-89
													05-Jul-89
					616.7	15.5	66.7	14.3	32.5	22.5	18.3	15.5	06-Jul-89
													07-Jul-89
													08-Jul-89
													09-Jul-89
		3.4	0.02	30.4									10-Jul-89
2.6	0.02				593.3	9.4	58.3	12.5	10.0	0.0	6.7	2.4	11-Jul-89
													12-Jul-89
													13-Jul-89
4.89	0.04												14-Jul-89
													15-Jul-89
													16-Jul-89
		3.8	0.06	28.9									17-Jul-89
5.0	0.02												18-Jul-89
													19-Jul-89

TKN mean	TKN std dev	NH4 mean	NH4 std dev	%NH4 REM'D	TS mean	TS std dev	TVS mean	TVS std dev	TSS mean	TSS std dev	TVSS mean	TVSS std dev	DATE
													20-Jul-89
5.0	0.04												21-Jul-89
													22-Jul-89
													23-Jul-89
		3.9	0.01	13.3									24-Jul-89
4.9	0.02												25-Jul-89
													26-Jul-89
													27-Jul-89
23.4	0.3												28-Jul-89
													29-Jul-89
													30-Jul-89
		15.0	0.10	-9.7									31-Jul-89
													01-Aug-89
													02-Aug-89
													03-Aug-89
													04-Aug-89
													05-Aug-89
													06-Aug-89
		24.2	0.34	-188.8									07-Aug-89
													08-Aug-89
													09-Aug-89
													10-Aug-89
													11-Aug-89
													12-Aug-89
													13-Aug-89
													14-Aug-89
													15-Aug-89
													16-Aug-89
													17-Aug-89
													18-Aug-89
													19-Aug-89
													20-Aug-89
													21-Aug-89
													22-Aug-89
													23-Aug-89
													24-Aug-89
													25-Aug-89

ROCK-REED FILTER DATA

SYSTEM TWO (SCIRPUS OR BULRUSH)

DATE	FLOWS (ml/min) IN	OUT	pH	WATER TEMP (oC)	ORP (mV) A	B	COD mean	std dev	%COD REM'D	BOD5 mean	std dev	COD /BOD5
12-Apr-89				23.5	280	295						
18-Apr-89					222	247						
20-Apr-89										4.8	0.1	
26-Apr-89	66											
27-Apr-89					-207	-67				3.6	0.2	
29-Apr-89	71		7.1									
01-May-89	70		7.1	25	-256	-146						
02-May-89	73			26	-197	-17						
03-May-89	74	65		25	-156	-86						
04-May-89	67	61			-245	-85						
05-May-89	70		7.1	21	-193	-93						
06-May-89				23	-235	-115						
07-May-89				24	-235	-95						
08-May-89	69		7.2	24	-235	-95						
09-May-89	70	46		25	-195	-116						
10-May-89	69			25	-216	-226						
11-May-89	72	37		22	-214	-214						
12-May-89	70	48		22	-214	-214						
13-May-89	70		6.9	23	-225	-215	175.0	5.1				
14-May-89	65			25	-236	-226	92.0	1.4				
15-May-89	71	39	7.1	26	-247	-227	85.0	23.9				
16-May-89	70	70	7	25	-236	-226	60.5	24.5	12.3			
17-May-89	67	62	7	25	-236	-146	24.0	0.0	64.5			
18-May-89	72	53	7.3	27	-247	-147	29.0	0.0	71.2			
19-May-89	71	66	7.2	25	-256	-145	34.0	5.0	60.0			
20-May-89	78	72	7.2	28	-248	-148	16.7	2.9	75.8			
21-May-89	80	78	7.3	27	-257	-137	13.3	3.3	79.8			
22-May-89	78	70	7.3	27	-237	-137	9.0	1.4	87.6			
23-May-89	74	74	7.4	27	-197	-147	13.0	4.5	82.7	2.5	0.3	5.3
24-May-89	90	80	7.2	28	-218	-148	35.3	11.9	57.9			
25-May-89	76	62		29	-199	-149	5.3	1.9	92.2			
26-May-89	78	70		29	-209	-139	8.3	2.9	73.6			
27-May-89	59		7.4	28	-248	-158	9.7	4.2				
28-May-89	82	62	7.2	29	-249	-239	32.0	1.4	83.5			
29-May-89	78	68	7.3	29	-209	-239	49.7	3.3	66.2			
30-May-89	80	76		28	-248	-238	37.7	6.0	81.0			
31-May-89	80	76	7.1	28	-248	-238	54.3	1.9	37.8	1.4	0.4	38.8
01-Jun-89	84	70	7.2	28	-248	-238	67.7	3.3	64.3			
02-Jun-89	76	76	7.1	26	-237	-237	0.0	0.0	100.0			
03-Jun-89	74	58	7.3	25	-236	-236	87.0	75.7	50.2			
04-Jun-89	77	58	7.2	26	-237	-227	54.3	2.9	80.3			
05-Jun-89	80	80	7.1	26	-227	-227						

DATE	FLOWS (ml/min) IN	OUT	pH	WATER TEMP (oC)	ORP (mV A	B	COD mean	std dev	%COD REM'D	BOD5 mean	std dev	COD /BOD5
06-Jun-89	76	56	7.1	26	-237	-237						
07-Jun-89	80	60	7.1	25	-236	-216						
08-Jun-89	78	72	7.1	26	-237	-167	60.3	1.9	7.2			
09-Jun-89	78	66	7.4	26	-177	-157	34.3	7.7	53.4			
10-Jun-89	78	74	7.1		-178	-158	12.7	9.0	90.5			
11-Jun-89	78	68	7.4	27	-167	-157	23.3	3.3	69.2			
12-Jun-89	80	74	7.3		-178	-168	24.7	2.9	51.5			
13-Jun-89	90	62	7.1	27	-177	-167	14.3	1.9	83.2			
14-Jun-89	76	72	7.1	27	-177	-177	18.0	1.4	72.3	5.0	1.2	3.6
15-Jun-89	70	60	7	26	-177	-177	24.7	3.3	66.6			
16-Jun-89	80	70	7.3		-178	-178	31.7	8.6	59.1			
17-Jun-89	84	66		27	-177	-177						
18-Jun-89	80	74		27	-157	-167						
19-Jun-89	80	70	7	28.5	-158	-168						
20-Jun-89	80	72	7	28	-168	-168						
21-Jun-89	80	70	6.8	28.5	-168	-178				4.5	1.1	
22-Jun-89	82	76	7.1	27	-167	-167						
23-Jun-89	84	74	6.8	27	-177	-167				4.3	0.2	
24-Jun-89	74	62		26	-167	-167						
25-Jun-89	78	68		27	-167	-167						
26-Jun-89	80	68		28	-167	-168						
27-Jun-89	86	76	7.1	28	-178	-178						
28-Jun-89												
29-Jun-89	82	62	7	29.5	-159	-189						
30-Jun-89	80	68	7	31	-170	-190				3.4	0.2	
01-Jul-89	80	66		28.5	-178	-178						
02-Jul-89	82	64		29.5	-139	-139						
03-Jul-89	80	64	6.8	27.5	-198	-188	1.6	0.6	97.3			
04-Jul-89	80	64	6.9	27	-198	-187						
05-Jul-89	80	64	6.9	26.5	-197	-187	23.2	1.6	72.9	4.7	0.5	5.0
06-Jul-89	78	70	7	27	-197	-207						
07-Jul-89	78	64	7.1	27.5	-198	-208	22.6	1.6	74.4	2.5	0.5	9.2
08-Jul-89	78	64		28	-198	-198						
09-Jul-89	80	64		29	-199	-209						
10-Jul-89	78	64	7	29	-209	-209	22.7	1.5	63.4			
11-Jul-89	80	64	6.7	28.5	-208	-198						
12-Jul-89	90	80	7	29.5	-219	-209	14.0	2.7	71.3	3.2	0.1	4.4
13-Jul-89	84	60	6.8	30	-219	-209						
14-Jul-89	82	64			-215	-195	11.5	3.3	80.0			
15-Jul-89	78	64			-228	-208						
16-Jul-89	80	64			-228	-218						
17-Jul-89	78	64			-229	-209	30.8	0.0	53.3			
18-Jul-89	78	66			-238	-218						
19-Jul-89	80	64	7.2		-249	-229	7.3	1.7	86.7	6.5	0.8	1.1

DATE	FLOW (ml/min) IN	OUT	pH	WATER TEMP(oC)	ORP (mV) A	B	COD (mg/l) mean	std dev	%COD REM'D	BOD5 (mg/l) mean	std dev	COD /BOD5
20-Jul-89	78	74	7	29	-245	-225			74.9			
21-Jul-89	74	50	7.2	27	-317	-287	18.3	2.9	96.2			
22-Jul-89	82	40		27	-347	-297						
23-Jul-89				26	-317	-287						
24-Jul-89	94	72	6.8	26	-277	-287	270.0	3.4	4.6			
25-Jul-89	86	68		27	-287	-277						
26-Jul-89	74	48	7	27	-287	-287						
27-Jul-89	82	60	7.1	29	-319	-299	183.1	6.2	40.5			
28-Jul-89	80	60	7.3	30	-319	-309	204.9	1.6	47.2			
29-Jul-89	124	110		28	-318	-308						
30-Jul-89	84	64		28.5	-318	-308						
31-Jul-89	70	50	7.2	29	-319	-309	155.6	6.5	52.6			
01-Aug-89	80	60	7.3	28	-318	-308						
02-Aug-89	50	40	7.2	28	-318	-308	127.6	1.6	65.5			
03-Aug-89	139	126	6.3	28.5	-318	-308				95.3	8.7	
04-Aug-89	110	92	7.3	29.5	-319	-319	193.2	1.6	48.5	136.3	24.6	1.4
05-Aug-89	81	66		29	-319	-319						
06-Aug-89	80	67		30	-319	-319						
07-Aug-89	80	66	7.3	30	-319	-319	200.0	1.6	38.7			
08-Aug-89	81	64	7.2	26	-307	-307						
09-Aug-89	83	71	7.4	26	-317	-317	166.1	2.9	49.2			
10-Aug-89	80	66	7.4	26	-317	-317						
11-Aug-89	86	67	6.6	26.5	-327	-317	126.6	3.2	63.9			
12-Aug-89	80	71		26.5	-327	-317						
13-Aug-89	84	79		27	-327	-317						
14-Aug-89	82	57		27	-327	-327						
15-Aug-89	79	76		27	-327	-327						
16-Aug-89	81	59		26.5	-337	-337						
17-Aug-89	82	56		27	-327	-327						
18-Aug-89	80	68		27.5	-328	-328						
19-Aug-89	82	49		27	-327	-327						
20-Aug-89	80	53		28	-328	-328						
21-Aug-89	82	49		28.5	-338	-328						
22-Aug-89	82	76		29	-339	-339	143.3	1.6	48.9	107.0	7.1	1.3
23-Aug-89	79	53		28.5	-338	-348		AVG 102-150.52				
24-Aug-89	80	53		29	-339	-339	61.3	1.9	78.0	31.0	5.9	2.0
25-Aug-89	79	61		28.5	-338	-338						

ROCK REED FILTER DATA

SYSTEM TWO (SCIRPUS OR BULRUSH)

TKN		NH4		%NH4	TS		TVS		TSS		TVSS		
mean	std dev	mean	std dev	REM'D	mean	std dev	mean	std dev	mean	std dev	mean	std dev	DATE
													12-Apr-89
													18-Apr-89
		1.9	0.2										20-Apr-89
					720.0	24.5	66.7	4.7	66.5	6.5	13.5	13.5	26-Apr-89
													27-Apr-89
					540.0	60.0	60.0	10.0	46.5	33.5	3.5	3.5	29-Apr-89
					560.0	14.1	26.7	12.5					01-May-89
													02-May-89
													03-May-89
					596.7	9.4	25.0	25.0	7.0	0.0	0.0	0.0	04-May-89
													05-May-89
													06-May-89
													07-May-89
													08-May-89
													09-May-89
													10-May-89
													11-May-89
													12-May-89
													13-May-89
													14-May-89
													15-May-89
													16-May-89
													17-May-89
													18-May-89
													19-May-89
													20-May-89
													21-May-89
													22-May-89
													23-May-89
		5.9	0.0	42.3									24-May-89
					600.0	14.1			16.7	6.2			25-May-89
													26-May-89
													27-May-89
													28-May-89
		6.1	0.1	3.4									29-May-89
					558.3	15.5			16.0	7.5			30-May-89
													31-May-89
					581.3	34.6	126.7	34.3	6.3	1.2			01-Jun-89
													02-Jun-89
													03-Jun-89
													04-Jun-89
		7.0	0.00										05-Jun-89

TKN		NH4		%NH4	TS		TVS		TSS		TVSS		
mean	std dev	mean	std dev	REM'D	mean	std dev	mean	std dev	mean	std dev	mean	std dev	DATE
					560.0	12.2	101.7	23.9	6.3	1.2	9.7	2.1	06-Jun-89
													07-Jun-89
					570.0	17.8	41.7	18.4	6.3	1.2	8.0	4.3	08-Jun-89
													09-Jun-89
													10-Jun-89
													11-Jun-89
													12-Jun-89
					638.3	42.9	10.0	4.1	6.3	1.2	277.3	0.5	13-Jun-89
													14-Jun-89
					616.7	32.7	16.7	2.4	6.3	1.2	274.7	3.3	15-Jun-89
6.3	0.05	5.0	0.1	42.8									16-Jun-89
													17-Jun-89
													18-Jun-89
													19-Jun-89
					575.0	29.4	85.0	20.4	6.3	1.2	5.7	0.9	20-Jun-89
													21-Jun-89
													22-Jun-89
					446.7	30.6	83.3	16.5	6.3	1.2			23-Jun-89
													24-Jun-89
													25-Jun-89
													26-Jun-89
					446.7	30.6	33.3	10.3	6.3	1.2	14.7	2.1	27-Jun-89
													28-Jun-89
					491.7	281.2	66.7	4.7	6.3	1.2	3.3	1.2	29-Jun-89
													30-Jun-89
													01-Jul-89
													02-Jul-89
													03-Jul-89
					606.7	13.1	135.0	7.1	24.0	7.9	12.0	4.1	04-Jul-89
													05-Jul-89
					626.7	16.5	65.0	4.1	6.3	1.2	5.0	2.0	06-Jul-89
													07-Jul-89
													08-Jul-89
													09-Jul-89
		2.8	0.00	44.5									10-Jul-89
2.2	0.02				463.3	168.5	50.0	12.2	6.3	1.2	6.7	2.4	11-Jul-89
													12-Jul-89
													13-Jul-89
4.0	0.00												14-Jul-89
													15-Jul-89
													16-Jul-89
		2.4	0.1	56.2									17-Jul-89
4.1	0.02												18-Jul-89
													19-Jul-89

TKN		NH4		%NH4	TS		TVS		TSS		TVSS		
mean	std dev	mean	std dev	REM'D	mean	std dev	mean	std dev	mean	std dev	mean	std dev	DATE
													20-Jul-89
4.1	0.02												21-Jul-89
													22-Jul-89
													23-Jul-89
		3.6	0.03	29.5									24-Jul-89
4.0	0.02												25-Jul-89
													26-Jul-89
													27-Jul-89
25.0	0.1												28-Jul-89
													29-Jul-89
													30-Jul-89
		18.6	0.50	-36.6									31-Jul-89
													01-Aug-89
													02-Aug-89
													03-Aug-89
													04-Aug-89
													05-Aug-89
													06-Aug-89
		24.2	0.50	-180.7									07-Aug-89
													08-Aug-89
													09-Aug-89
													10-Aug-89
													11-Aug-89
													12-Aug-89
													13-Aug-89
													14-Aug-89
													15-Aug-89
													16-Aug-89
													17-Aug-89
													18-Aug-89
													19-Aug-89
													20-Aug-89
													21-Aug-89
													22-Aug-89
													23-Aug-89
													24-Aug-89
													25-Aug-89

ROCK-REED FILTER DATA

SYSTEM THREE (CONTROL)

DATE	FLOWS (ml/min) IN	OUT	pH	WATER TEMP (oC)	ORP (mV A	B	COD mean	std dev	%COD REM'D	BOD5 mean	std dev	COD /BOD5
12-Apr-89					420	455						
18-Apr-89					447	223						
20-Apr-89										5.1	1.2	
26-Apr-89	70											
27-Apr-89					-287	-237				2.9	0.1	
29-Apr-89	71		7.5									
01-May-89	70		7.5	26	-276	-276						
02-May-89	71			27	-267	-277						
03-May-89	71	66		24	-195	-225						
04-May-89	71	61			-265	-205						
05-May-89	74		7.3	21	-263	-223						
06-May-89					-275	-245						
07-May-89				24	-245	-185						
08-May-89	70		7.5	24	-255	-245						
09-May-89	70	55		25	-256	-256						
10-May-89	70			25	-236	-266						
11-May-89	73	73		21	-224	-234						
12-May-89	72			22	-204	-234						
13-May-89	73		7.1	23	-225	-225	154.3	6.1				
14-May-89	64			26	-227	-247	114.0	0.0				
15-May-89	69	69	7.2	26	-247	-247	121.0	3.0				
16-May-89	72	85	7.5	25	-256	-256	88.0	0.0	-50.6			
17-May-89	56	87	7.5	25	-256	-256	74.5	3.5	-85.2			
18-May-89	69	85	7.8	27	-267	-267	52.0	3.0	13.4			
19-May-89	70	68	7.7	25	-256	-196	49.0	0.0	39.7			
20-May-89	76	76	7.7	28	-258	-208	26.0	1.4	59.2			
21-May-89	80	70	7.8	28	-237	-237	28.3	2.9	61.6			
22-May-89	84	84	7.7	27	-217	-197	37.7	1.9	42.1			
23-May-89	64	60	7.7	28	-194	-199	27.0	1.4	66.3			
24-May-89	80	80	7.7	28	-208	-198	33.7	4.1	54.9			
25-May-89	74	76		29	-219	-199	23.0	1.4	57.8			
26-May-89	80	74		30	-259	-209	29.3	6.1	4.2			
27-May-89	78		7.9	29	-249	-230	34.7	6.0				
28-May-89	78	80	7.7	30	-249	-269	57.0	1.4	60.1			
29-May-89	78	78	7.8	29	-249	-259	84.3	1.9	34.1			
30-May-89	82	88		28	-248	-248	84.3	2.9	51.9			
31-May-89	82	88	7.4	28	-258	-258	95.3	2.9	-23.3	1.5	0.1	63.6
01-Jun-89	78	80	7.4	28	-248	-258	146.3	43.7	5.0			
02-Jun-89	80	84	7.4	25	-236	-256						
03-Jun-89	0	0		25.5	-236	-246						
04-Jun-89	0	0		26	-237	-247						
05-Jun-89	0	0		25	-236	-246						

	FLOWS (ml/min)			WATER	ORP (mV)		COD		%COD	BOD5		COD
DATE	IN	OUT	pH	TEMP (oC)	A	B	mean	std dev	REM'D	mean	std dev	/BOD5
06-Jun-89	70	66		26	-247	-257						
07-Jun-89	92	86	7.3	26	-247	-257						
08-Jun-89	80	70	7.6	27	-217	-257	88.3	2.9	-28.8			
09-Jun-89	78	75	7.8	26	-207	-247	56.7	5.2	12.6			
10-Jun-89	90	84	7.8	28	-218	-198	49.0	1.4	63.9			
11-Jun-89	72	74	7.9	27	-217	-197	43.0	3.3	33.0			
12-Jun-89	96	94	8		-218	-218	78.7	39.3	-63.9			
13-Jun-89	62	60	7.4	27	-217	-207	33.0	1.4	45.6			
14-Jun-89	78	78	8	27	-217	-207	33.0	0.0	46.5	13.8	0.2	
15-Jun-89	76	70	7.8	26	-217	-217	54.0	1.4	21.5			
16-Jun-89	68	64	7.9		-218	-208	60.7	8.7	15.6			
17-Jun-89	76	70		27	-207	-207	39.9	10.4	39.8			
18-Jun-89	76	74		27	-217	-197						
19-Jun-89	84	72	8.2	28.5	-218	-198						
20-Jun-89	80	68	7.9	27.5	-218	-198						
21-Jun-89	60	52	7.5	28	-168	-158				11.8	0.5	
22-Jun-89	78	68	7.5	27	-217	-197						
23-Jun-89	64	58		27	-207	-187				11.0	0.3	
24-Jun-89	80	72		26	-197	-177						
25-Jun-89	80	72		27	-207	-207						
26-Jun-89	66	58		27.5	-208	-208						
27-Jun-89	78	68	7.9	27.5	-198	-188						
28-Jun-89												
29-Jun-89	86	80	7.8	30	-259	-179						
30-Jun-89	94	82	8	32	-231	-201				9.4	0.2	
01-Jul-89	80	74		28.5	-208	-188						
02-Jul-89	86	70		29.5	-219	-209						
03-Jul-89	78	74	7.5	27.5	-208	-208	21.3	1.7	58.4			
04-Jul-89	78	62	7.7	27	-217	-207						
05-Jul-89	83	60	8	26.5	-217	-217	48.8	2.9	48.6	13.0	0.8	3.8
06-Jul-89	80	66	7.8	27	-227	-217						
07-Jul-89	80	74	8.1	27	-237	-237	41.8	1.6	46.5	14.5	1.8	2.9
08-Jul-89	78	70		27.5	-237	-218						
09-Jul-89	82	76		29	-229	-219						
10-Jul-89	78	70	7.8	29	-239	-229	48.8	1.5	14.1			
11-Jul-89	78	70	7.8	28	-228	-218						
12-Jul-89	70	64	7.8	29.5	-229	-219	44.5	1.6	6.3	18.3	0.6	2.4
13-Jul-89	78	70		30	-239	-219						
14-Jul-89	78	70			-219	-209	31.1	3.3	37.9			
15-Jul-89	78	70			-218	-208						
16-Jul-89	78	70			-208	-198						
17-Jul-89	78	70			-239	-239	30.0	0.0	50.2			
18-Jul-89	78	70			-238	-238						
19-Jul-89	76	68	8.1		-259	-249	4.8	2.9	90.2	17.1	1.3	0.3

DATE	FLOW (ml/min) IN	OUT	pH	WATER TEMP(oC)	ORP (mV) A	B	COD (mg/l) mean	std dev	%COD REM'D	BOD5 (mg/l) mean	std dev	COD /BOD5
20-Jul-89	80	72	7.7	29	-255	-245			44.0			
21-Jul-89	60	58	7.9	27	-317	-297	31.0	13.0	90.7			
22-Jul-89	80	82		27	-327	-337						
23-Jul-89				27	-317	-327						
24-Jul-89	70	54	7.3	27	-277	-327	264.0	6.1	6.1			
25-Jul-89	84	72		27	-257	-297						
26-Jul-89	70	70	7.3	28	-298	-298						
27-Jul-89	82	78	7.3	31	-320	-310	212.3	3.3	10.3			
28-Jul-89	80	76	7.5	30	-319	-319	214.1	4.9	30.1			
29-Jul-89	80	70		28	-318	-318						
30-Jul-89	80	72		28.5	-318	-318						
31-Jul-89	70	70	7.4	29	-329	-329	171.7	25.9	26.8			
01-Aug-89	74	76	7.5	28	-318	-328						
02-Aug-89	80	80	7.3	30	-319	-329	209.2	1.6	29.2			
03-Aug-89	80	70	7	28.5	-318	-318				97.4	2.9	
04-Aug-89	80	70	7.6	29.5	-319	-329	230.0	4.3	35.9	99.4	2.9	2.3
05-Aug-89	81	70		29	-319	-319						
06-Aug-89	86	81		30	-319	-329						
07-Aug-89	81	71	7.5	30	-319	-329	217.6	1.6	29.1			
08-Aug-89	84	76	7.6	26	-317	-327						
09-Aug-89	80	72	7.8	25.5	-326	-326	188.3	1.6	39.4			
10-Aug-89	84	75	7.6	25.5	-326	-336						
11-Aug-89	84	72	7.3	26	-337	-347	202.2	4.2	36.6			
12-Aug-89	79	67		26	-327	-337						
13-Aug-89	84	80		26.5	-337	-347						
14-Aug-89	81	74		27	-337	-347						
15-Aug-89	80	73		27	-337	-347						
16-Aug-89	82	78		26.5	-337	-347						
17-Aug-89	81	71		27	-338	-338						
18-Aug-89	82	78		27	-347	-337						
19-Aug-89	82	80		27	-337	-347						
20-Aug-89	82	75		28	-337	-348						
21-Aug-89	81	75		28.5	-338	-348						
22-Aug-89	81	81		29	-339	-349	186.7	1.6	28.2	175.7	11.9	1.1
23-Aug-89	79	71		28.5	-338	-348			32.94			
24-Aug-89	83	75		29	-339	-349	128.0	3.3	36.7	77.0	8.0	1.7
25-Aug-89	79	71		28.5	-338	-348						

ROCK REED FILTER DATA

SYSTEM THREE (CONTROL)

TKN mean	TKN std dev	NH4 mean	NH4 std dev	%NH4 REM'D	TS mean	TS std dev	TVS mean	TVS std dev	TSS mean	TSS std dev	TVSS mean	TVSS std dev	DATE
													12-Apr-89
													18-Apr-89
		10.3	0.9										20-Apr-89
					623.3	30.9	60.0	10.0	13.0	0.0	6.5	6.5	26-Apr-89
													27-Apr-89
					510.0	40.0	70.0	0.0	31.0	15.6	6.5	6.5	29-Apr-89
													01-May-89
													02-May-89
													03-May-89
													04-May-89
													05-May-89
													06-May-89
													07-May-89
													08-May-89
													09-May-89
													10-May-89
													11-May-89
													12-May-89
													13-May-89
													14-May-89
													15-May-89
													16-May-89
													17-May-89
													18-May-89
													19-May-89
													20-May-89
													21-May-89
													22-May-89
													23-May-89
		9.5	0.3	-5.5									24-May-89
													25-May-89
													26-May-89
													27-May-89
													28-May-89
													29-May-89
													30-May-89
													31-May-89
					556.0	5.7	102.7	6.8					01-Jun-89
													02-Jun-89
													03-Jun-89
													04-Jun-89
													05-Jun-89

TKN		NH4		%NH4	TS		TVS		TSS		TVSS		
mean	std dev	mean	std dev	REM'D	mean	std dev	mean	std dev	mean	std dev	mean	std dev	DATE
					540.0	8.2	98.3	8.5	68.3	28.7	9.7	2.1	06-Jun-89
													07-Jun-89
					546.7	6.2	41.7	8.5	13.0	5.7	5.7	3.3	08-Jun-89
													09-Jun-89
													10-Jun-89
													11-Jun-89
													12-Jun-89
													13-Jun-89
													14-Jun-89
													15-Jun-89
9.8	0.05	3.3	0.05	58.7									16-Jun-89
													17-Jun-89
													18-Jun-89
													19-Jun-89
													20-Jun-89
													21-Jun-89
													22-Jun-89
													23-Jun-89
													24-Jun-89
													25-Jun-89
													26-Jun-89
													27-Jun-89
													28-Jun-89
													29-Jun-89
													30-Jun-89
													01-Jul-89
													02-Jul-89
													03-Jul-89
					533.3	29.5	136.7	20.5	17.3	2.1	14.0	1.4	04-Jul-89
													05-Jul-89
					588.3	10.3	76.7	12.5					06-Jul-89
													07-Jul-89
													08-Jul-89
													09-Jul-89
		8.1	0.11	-73.5									10-Jul-89
4.9	0.02												11-Jul-89
													12-Jul-89
													13-Jul-89
9.2	0.02												14-Jul-89
													15-Jul-89
													16-Jul-89
		7.5	0.05	-50.7									17-Jul-89
6.0	0.10												18-Jul-89
													19-Jul-89

TKN		NH4		%NH4	TS		TVS		TSS		TVSS		
mean	std dev	mean	std dev	REM'D	mean	std dev	mean	std dev	mean	std dev	mean	std dev	DATE
													20-Jul-89
9.5	0.09												21-Jul-89
													22-Jul-89
													23-Jul-89
		6.9	0.04	-33.8									24-Jul-89
9.1	0.10												25-Jul-89
													26-Jul-89
													27-Jul-89
25.9	0.00												28-Jul-89
													29-Jul-89
													30-Jul-89
		25.8	0.20	-164.6									31-Jul-89
													01-Aug-89
													02-Aug-89
													03-Aug-89
													04-Aug-89
													05-Aug-89
													06-Aug-89
		28.7	0.49	-253.9									07-Aug-89
													08-Aug-89
													09-Aug-89
													10-Aug-89
													11-Aug-89
													12-Aug-89
													13-Aug-89
													14-Aug-89
													15-Aug-89
													16-Aug-89
													17-Aug-89
													18-Aug-89
													19-Aug-89
													20-Aug-89
													21-Aug-89
													22-Aug-89
													23-Aug-89
													24-Aug-89
													25-Aug-89

Data from Eighty-Day Variable Loading Investigation

ROCK-REED FILTER DATA

FEED RESERVOIR

DATE	AIR TEMP (oC) low	high	avg	pH	COD (mg/l) mean	std dev	BOD5(mg/l) mean	std dev	COD /BOD5	TKN (mg/l) mean	std dev	NH4 (mg/l) mean	std dev
26-Aug-89	80	94	87	7.3									
27-Aug-89	79	95	87	7.3	82	1.5	23	7.0	3.5				
28-Aug-89	80	96	88	7.3									
29-Aug-89	79	95	87	7.4	69	5.4	20	4.1	3.5	10.9	0.05	2.7	0.15
30-Aug-89	79	94	86.5	7.4									
31-Aug-89	80	90	85	7.4	55	4.5	18	3.3	3.1				
01-Sep-89	80	100	90	7.6									
02-Sep-89	80	96	88		69	2.8	24	1.5	2.9	12.0	0.21	1.8	0
03-Sep-89	80	98	89		65	1.9	24	5.2	2.7				
04-Sep-89	78	102	90	7.3	78	1.5				11.5	0.08	4.1	0.33
				AVG	70		22		3.1	11.4			
05-Sep-89	78	98	88	7.4									
06-Sep-89	78	96	87	7.3	212	2.9	61	1.5	3.5				
07-Sep-89	78	101	89.5	7.3									
08-Sep-89	78	98	88	7.6	153	0.0	85	5.2	1.8	22.4	0	1.4	0.05
09-Sep-89	78	99	88.5	7.2									
10-Sep-89	79	100	89.5	7.1	217	1.9							
11-Sep-89	77	95	86	7.5									
12-Sep-89	76	100	88	7	206	1.3	131	1.4	1.6			7.9	0.70
13-Sep-89	77	98	87.5	7	228	4.1							
14-Sep-89	78	98	88	6.9	259	1.4	115	0.9	2.2	28.4	0.00	4.8	0.32
				AVG	213	1.3	98		2.3				
15-Sep-89	73	93	83										
16-Sep-89	70	82	76		274	1.4							
17-Sep-89	70	90	80										
18-Sep-89	70	95	82.5		287	11.0							
19-Sep-89	71	94	82.5										
20-Sep-89	72	94	83		245	2.9							
21-Sep-89	72	82	77										
22-Sep-89	73	86	79.5		278	6.6	102	5.8	2.7	38.0	0.4	6.2	0.14
23-Sep-89	72	84	78		253	1.9							
24-Sep-89	70	85	77.5		305	12.7				40.0	0.9	6.5	0.70
				AVG	274		102		2.7				
25-Sep-89	70	78	74										
26-Sep-89	69	80	74.5		101	3.3							
27-Sep-89	70	82	76										

	AIR TEMP (oC)				COD (mg/l)		BOD5(mg/l)		COD	TKN (mg/l)		NH4 (mg/l)	
DATE	low	high	avg	pH	mean	std dev	mean	std dev	/BOD5	mean	std dev	mean	std dev
28-Sep-89	71	82	76.5	6.9	120	2.4	68	5.1	1.8	20.2	0.1	2.2	0.14
29-Sep-89	71	78	74.5										
30-Sep-89	70	84	77	7.2	125	3.7							
01-Oct-89	70	85	77.5	7.4									
02-Oct-89	70	84	77	7.5	147	3.3	41	6.2	3.6	19.8	0.6	0.0	0.00
03-Oct-89					141	3.3	85	26.9	1.7				
04-Oct-89	73	90	81.5	8	107	1.4	64	9.9	1.7	13.4	0.7	0.0	0.00
				AVG	123		64		2.2				
05-Oct-89	70	85	77.5	7.3									
06-Oct-89	72	88	80	7.3	225	0.0							
07-Oct-89	73	94	83.5	7.5									
08-Oct-89	72	88	80	7.5	227	1.4	87	3.0	2.6	29.6	0.1	0.0	0.00
09-Oct-89	69	87	78	7.5									
10-Oct-89	69	84	76.5	7.2	252	1.9							
11-Oct-89	70	87	78.5	7.5									
12-Oct-89	70	87	78.5	7.5	185	1.4	113	1.6	1.6	27.1	0.2	2.7	0.24
13-Oct-89	72	90	81	7.4	210	2.4							
14-Oct-89	72	86	79	7.4	159	1.4	84	1.0	1.9	24.5	0.2	1.1	0.80
				AVG	210		95		2.0				
15-Oct-89	72	84	78	7.5									
16-Oct-89	77	90	83.5	7.6	69	3.8							
17-Oct-89	75	90	82.5	7.2									
18-Oct-89	70	78	74	7.4	84	3.3	27	0.8	3.2	9.6	0	0.3	0.15
19-Oct-89	67	79	73	7.5									
20-Oct-89	66	85	75.5	7.5	94	2.8							
21-Oct-89	83	78	80.5	7.3									
22-Oct-89	68	85	76.5	7.3	95	1.4				11.1	0.1	1.3	0.28
23-Oct-89	68	85	76.5	7.7	83	4.2							
24-Oct-89	79	85	82	7.2	60	0.0	21	4.0	2.9	8.3	0	1.1	0.14
				AVG	81		24		3.0				
25-Oct-89	70	88	79	7.7									
26-Oct-89	68	88	78	7.3	247	1.9							
27-Oct-89	70	86	78	7.7									
28-Oct-89	69	87	78	7.1	356	1.9				41.9	0.46	1.6	0
29-Oct-89	69	87	78										
30-Oct-89	69	88	78.5		320	4.7							
31-Oct-89	70	84	77	6.4									
01-Nov-89	69	86	77.5		333	15.1				37.0	0.5	0.9	0
02-Nov-89	68	82	75		270	1.9	54	7.4	5.0				

	AIR TEMP (oC)				COD (mg/l)		BOD5(mg/l)		COD	TKN (mg/l)		NH4 (mg/l)	
DATE	low	high	avg	pH	mean	std dev	mean	std dev	/BOD5	mean	std dev	mean	std dev
03-Nov-89	67	90	78.5		313	9.0	96	18.5	3.3	28.8	0.0	7.7	0
				AVG	306		75		4.1				
04-Nov-89	64	84	74										
05-Nov-89	68	90	79		151	3.8							
06-Nov-89	72	90	81	7.3									
07-Nov-89	72	88	80	7.1	132	1.9	89	1.4	1.5	12.3	0.14	0.9	0
08-Nov-89	74	80	77	7.2									
09-Nov-89	69	86	77.5	7.3	132	1.4							
10-Nov-89	68	94	81	7.3									
11-Nov-89	70	88	79	7.2	191	2.8	66	1.2	2.9	15.6	0.14	0.0	0
12-Nov-89	68	90	79	7.6	133	6.2	68	2.0	2.0				
13-Nov-89	70	85	77.5		190	11.3		1.2				7.7	0.21
	73	89	81		155		74		2.1				
	4.3	6.2	4.7										
		MIN	73										
		MAX	90					GRD TOT	2.7				
								STD DEV	0.7				

ROCK-REED FILTER DATA

FEED RESERVOIR

org-N	TS (mg/l)		TVS (mg/l)		TSS (mg/l)		TVSS (mg/l)		FRAC'N	
(mg/l)	mean	std dev	mean	std dev	mean	std dev	mean	std dev	DS/TS	DATE
										26-Aug-89
										27-Aug-89
										28-Aug-89
8.2	520.0	26.8	65.0	16.3	21.7	7.7	8.3	2.4	0.87	29-Aug-89
										30-Aug-89
										31-Aug-89
										01-Sep-89
10.2	508.3	116.1	81.7	27.2	39.3	6.2	30.7	2.5	0.62	02-Sep-89
										03-Sep-89
7.4	600.0	0.0	115.0	5.0	69.3	9.4	34.0	4.3	0.70	04-Sep-89
	542.8		87.2		43.4		24.3			
										05-Sep-89
										06-Sep-89
										07-Sep-89
21.0	460	20.4	133	6.2	75	5.2	55	1.9	0.59	08-Sep-89
										09-Sep-89
										10-Sep-89
										11-Sep-89
	3995	394.4	1575	159.4	57	5.2	35	2.5	0.98	12-Sep-89
										13-Sep-89
23.6										14-Sep-89
										15-Sep-89
										16-Sep-89
										17-Sep-89
	833	23.2								18-Sep-89
										19-Sep-89
										20-Sep-89
										21-Sep-89
31.8										22-Sep-89
										23-Sep-89
33.5										24-Sep-89
										25-Sep-89
										26-Sep-89
										27-Sep-89

org-N	TS (mg/l)		TVS (mg/l)		TSS (mg/l)		TVSS (mg/l)		FRAC'N	
(mg/l)	mean	std dev	mean	std dev	mean	std dev	mean	std dev	DS/TS	DATE
18.0	553	16.5	42	4.7	21	1.9	11	1.9	0.73	28-Sep-89
										29-Sep-89
										30-Sep-89
										01-Oct-89
19.8	613	13.1	85	12.2	40	5.0	10	5.0	0.88	02-Oct-89
										03-Oct-89
13.4										04-Oct-89
										05-Oct-89
										06-Oct-89
										07-Oct-89
29.6										08-Oct-89
										09-Oct-89
										10-Oct-89
										11-Oct-89
24.4										12-Oct-89
										13-Oct-89
23.3										14-Oct-89
										15-Oct-89
										16-Oct-89
										17-Oct-89
9.4										18-Oct-89
										19-Oct-89
										20-Oct-89
										21-Oct-89
9.8										22-Oct-89
										23-Oct-89
7.2										24-Oct-89
										25-Oct-89
										26-Oct-89
										27-Oct-89
40.3										28-Oct-89
										29-Oct-89
										30-Oct-89
										31-Oct-89
36.1										01-Nov-89
										02-Nov-89

org-N (mg/l)	TS (mg/l) mean	std dev	TVS (mg/l) mean	std dev	TSS (mg/l) mean	std dev	TVSS (mg/l) mean	std dev	FRAC'N DS/TS	DATE
21.1										03-Nov-89
										04-Nov-89
										05-Nov-89
										06-Nov-89
11.4	510	134	72	22	27	2	1	1	0.99	07-Nov-89
										08-Nov-89
										09-Nov-89
										10-Nov-89
15.6										11-Nov-89
										12-Nov-89
	1218	19	287	57	23	5	6	2	0.98	13-Nov-89

AVG TVDS/TVS 0.82
STD DEV TVDS/ 0.15

ROCK-REED FILTER DATA

SYSTEM ONE (SAGITTARIA OR ARROWROOT)

	FLOWS (ml/min)			WATER	ORP (mV)		COD (mg/l)		%COD	BOD5		%BOD	COD
DATE	IN	OUT	pH	TEMP(oC)	A	B	mean	std dev	REM'D	mean	std dev	REM'D	/BOD5
26-Aug-89	81	72	7.4	29	-369	-349							
27-Aug-89	80	68	7.4	28.5	-348	-358	79	0	4%	16	1.0	38%	5.0
28-Aug-89	80	64	7.4	30	-339	-279							
29-Aug-89	81	80	7.6	28.5	-328	-278	46	0	44%	15	3.3	43%	3.1
30-Aug-89	81	77	7.4	29.5	-339	-279							
31-Aug-89	79	60	7.6	30	-329	-269	18	3	78%	9	4.2	65%	2.0
01-Sep-89	79	56	7.5	30	-329	-269							
02-Sep-89	82	74		30.5	-340	-280	23	5	72%	12	0.6	54%	2.0
03-Sep-89	82	69		30.5	-330	-280	31	5	62%	9	0.8	66%	3.6
04-Sep-89	79	60	7.5	29	-339	-279	29	3	64%	7	0.3	73%	4.2
	80	68							54%		AVG	56%	3.3
									24.7%		STD	12.8%	
05-Sep-89	80	71	7.5	29	-339	-279							
06-Sep-89	82	64	7.6	28	-358	-338	48	1.5	81%	17	2.0	85%	2.8
07-Sep-89	81	73	7.6	28.5	-358	-338							
08-Sep-89	80	65	7.5	28	-378	-348	99	2.8	60%	38	3.9	67%	2.6
09-Sep-89	80	71	7.4	29	-389	-359							
10-Sep-89	80	70	7.4	29.5	-379	-359	122	11.6	51%				
11-Sep-89	80	58	7.5	28.5	-378	-358							
12-Sep-89	84	81	7.3	28	-379	-358	101	2.8	59%				
13-Sep-89	81	70	7.4	27.5	-378	-358	101	2.9	59%				
14-Sep-89	79	68	7.4	29	-379	-359	123	2.8	50%	25	0.8	78%	4.9
	81	69							60%		AVG	77%	3.5
									10.0%		STD	7.4%	
15-Sep-89	79	74		26	-367	-347							
16-Sep-89	77.5	60		24	-375	-355	118	0	63%				
17-Sep-89	79.5	62		25	-376	-356							
18-Sep-89	80	68		25	-386	-366	115	0	64%				
19-Sep-89	79	74		25.5	-386	-366							
20-Sep-89	80	64		25.5	-356	-356	120	2	63%				
21-Sep-89	82	78		25.5	-376	-356							
22-Sep-89	82	70		25	-376	-356	132	21	59%	58	0.9	51%	2.3
23-Sep-89	82	66		25	-376	-356	139	3	57%				
24-Sep-89	81	72		23.5	-385	-365	166	7	48%				
	80	69							59%		AVG	51%	2.3
									5.5%		STD		
25-Sep-89	80	80		23	-385	-365							
26-Sep-89	81	74		23.5	-365	-365	114	0	20%				
27-Sep-89	79	70		23	-355	-355							

DATE	FLOWS (ml/min) IN	OUT	pH	WATER TEMP(oC)	ORP (mV) A	B	COD (mg/l) mean	std dev	%COD REM'D	BOD5 mean	std dev	%BOD REM'D	COD /BOD5
28-Sep-89	80	74	7.1	23.5	-375	-345	72	1.5	49%	40	8.6	47%	1.8
29-Sep-89	79	90		23	-365	-335							
30-Sep-89	80	72	7.7	22.5	-384	-334	68	1.5	52%				
01-Oct-89	81	70	7.8	23	-355	-335							
02-Oct-89	79	64	7.6	24	-365	-355	75	3.5	48%	33	2.5	55%	2.2
03-Oct-89							87	0.0	39%	30	2.5	60%	2.9
04-Oct-89	79	28	7.7	27	-387	-347	62	5.0	56%	28	0.9	63%	2.3
	80	69							44%		AVG	56%	2.3
									12.0%		STD	6.0%	
05-Oct-89	140	120	7.8	25.5	-386	-346							
06-Oct-89	139	132	7.6	25.5	-366	-366	95	1.4	57%				
07-Oct-89	135	122	7.6	27	-397	-367							
08-Oct-89	138	130	7.6	25	-386	-386	125	1.5	44%	42	5.7	59%	3.0
09-Oct-89	140	130	7.9	23.5	-425	-405							
10-Oct-89	140	136	7.7	23.5	-435	-415	33	1.4	85%				
11-Oct-89	140	138	7.8	24	-435	-435							
12-Oct-89	140	140	7.8	24	-455	-445	105	1.9	53%	45	2.1	55%	2.3
13-Oct-89	139	128	7.8	25	-466	-436	79	1.9	64%	37	1.4	63%	
14-Oct-89	140	134	7.8	24.5	-476	-446	87	1.4	61%	44	5.5	56%	2.0
	139	131							61%		AVG	58%	2.4
									12.6%		STD	3.2%	
15-Oct-89	141	140	7.5	24.5	-446	-436							
16-Oct-89	140	130	7.8	26	-417	-417	63	0.0	29%				
17-Oct-89	140	128	7.8	26.5	-367	-417							
18-Oct-89	142	128	7.7	23.5	-415	-415	55	3.8	39%				
19-Oct-89	141	128	7.8	22	-434	-414							
20-Oct-89	140	125	7.8	21	-423	-413	34	2.9	61%				
21-Oct-89	141	130	7.7	21.5	-424	-424							
22-Oct-89	140	132	7.7	22.5	-424	-424	47	1.4	47%	20	0.5	24%	2.4
23-Oct-89	139	100	7.8	23	-415	-415	45	5.3	50%				
24-Oct-89	140	134	7.8	23.5	-415	-415	41	0.9	54%	12	0.9	53%	3.3
	140	128					47		47%		AVG	39%	2.8
									10.6%		STD	14.3%	
25-Oct-89	139	120	7.8	23	-415	-405							
26-Oct-89	139	132	7.7	23	-475	-445	79	0.0	78%				
27-Oct-89	140	120	7.7	23	-455	-455							
28-Oct-89			7.7	23	-435	-505	101	1.4	72%				
29-Oct-89	140	130		23	-435	-455							
30-Oct-89	138	116		23	-465	-445	110	4.2	69%				
31-Oct-89	140	136	6.7	23	-465	-465							
01-Nov-89	135	80		22	-454	-454	135	12.7	62%				
02-Nov-89	141	136		22.5	-454	-454	137	1.9	61%	33	1.6	62%	4.1

DATE	FLOWS (ml/min) IN	OUT	pH	WATER TEMP(oC)	ORP (mV) A	B	COD (mg/l) mean	std dev	%COD REM'D	BOD5 mean	std dev	%BOD REM'D	COD /BOD5
03-Nov-89	138	110		22	-444	-444	82	6.5	77%	47	7.5	46%	1.8
	139	120							70%		AVG	54%	2.9
									6.4%		STD	7.9%	
04-Nov-89	140	130		21.5	-434	-454							
05-Nov-89	140	134		21.5	-434	-404	88	1.9	50%				
06-Nov-89	140	123	7.3	24.5	-437	-436							
07-Nov-89	141	130	6.8	25.5	-456	-446	93	1.9	47%	36	1.9	58%	2.6
08-Nov-89	140	124	7.4	24.5	-436	-436							
09-Nov-89	141	138	7.5	24	-445	-435	72	1.4	59%				
10-Nov-89	141	110	7.4	23	-425	-435							
11-Nov-89	141	120	7.3	21.5	-464	-434	73	4.2	59%	21	0.5	76%	3.5
12-Nov-89	139	110	7.6	23	-425	-445	69	1.4	61%	16	0.9	81%	4.4
13-Nov-89	140	112		23	-405	-445	72	3.8	59%	29	1.7	65%	2.5
	140	123							56%		AVG	70%	3.3
									5.3%		STD	9.1%	
									56%		GRD TOT	58%	2.9
									7.7%		STD DEV	10.9%	0.4

ROCK REED FILTER DATA

SYSTEM ONE (SAGITTARIA OR ARROWROOT)

TKN mean	TKN std dev	NH4 mean	NH4 std dev	%TKN REM'D	org-N (mg/l)	TS mean	TS std dev	TVS mean	TVS std dev	TSS mean	TSS std dev	TVSS mean	TVSS std dev	DATE
														26-Aug-89
														27-Aug-89
														28-Aug-89
17.5	0.2	10.0	2.82		7.5	601.7	23.9	53.3	22.5	15.8	2.4	2.5	3.5	29-Aug-89
														30-Aug-89
														31-Aug-89
														01-Sep-89
12.8	0.09	5.7	0.51	10%	7.1	505.0	64.8	71.7	16.5	29.3	7.5	16.7	2.5	02-Sep-89
														03-Sep-89
10.6	0	9.3	0.56	22%	1.3	563.3	29.0	75.0	10.8	32.0	1.6	17.3	5.2	04-Sep-89
				16%										
														05-Sep-89
														06-Sep-89
														07-Sep-89
22.4	2.29	15.7	0.19	14%	6.7	545	14.7	97	8.5	35	2.5	17	5.7	08-Sep-89
														09-Sep-89
														10-Sep-89
														11-Sep-89
28.3	0.48	19.5	1.95		8.8	3732	351.4	1382	53.9	31	2.5	11	3.4	12-Sep-89
														13-Sep-89
28.2	0.28	15.2	0.78	15%	13.0									14-Sep-89
				15%										
														15-Sep-89
														16-Sep-89
														17-Sep-89
						688	35.2							18-Sep-89
														19-Sep-89
														20-Sep-89
														21-Sep-89
25.7	0.3	29.2	0.42	42%	-3.5									22-Sep-89
														23-Sep-89
34.3	1.0	31.5	0.57	26%	2.8									24-Sep-89
				34%										
														25-Sep-89
														26-Sep-89
														27-Sep-89

TKN mean	TKN std dev	NH4 mean	NH4 std dev	%TKN REM'D	org-N (mg/l)	TS mean	TS std dev	TVS mean	TVS std dev	TSS mean	TSS std dev	TVSS mean	TVSS std dev	DATE
22.1	0.3	19.5	0.00	5%	2.6	505	20.4	45	4.1	125	0	5	0	28-Sep-89
														29-Sep-89
														30-Sep-89
														01-Oct-89
18.6	0.5	16.1	0.33	19%	2.4	542	8.5	57	2.4	4	0	4	0	02-Oct-89
														03-Oct-89
20.2	0.0	15.0	0.94		5.2									04-Oct-89
				12%										
														05-Oct-89
														06-Oct-89
														07-Oct-89
27.0	0.2	20.5	0.82	14%	6.5									08-Oct-89
														09-Oct-89
														10-Oct-89
														11-Oct-89
25.3	0.3			12%	25.3									12-Oct-89
														13-Oct-89
23.7	0.1	20.1	0.45	9%	3.6									14-Oct-89
				12%										
														15-Oct-89
														16-Oct-89
														17-Oct-89
11.1	0.4	9.5	0.14		1.6									18-Oct-89
														19-Oct-89
														20-Oct-89
														21-Oct-89
9.9	0.1	8.8	0.00	19%	1.1									22-Oct-89
														23-Oct-89
8.7	0.1	7.6	0.09	5%	1.1									24-Oct-89
				12%										
														25-Oct-89
														26-Oct-89
														27-Oct-89
23.0	0.0	27.2	0.09	53%	-4.2									28-Oct-89
														29-Oct-89
														30-Oct-89
														31-Oct-89
29.5	0.6			31%	29.5									01-Nov-89
														02-Nov-89

TKN mean	TKN std dev	NH4 mean	NH4 std dev	%TKN REM'D	org-N (mg/l)	TS mean	TS std dev	TVS mean	TVS std dev	TSS mean	TSS std dev	TVSS mean	TVSS std dev	DATE
32.9	0.7	33.8	1.32	1%	-0.9									03-Nov-89
				28%										
														04-Nov-89
														05-Nov-89
														06-Nov-89
11.1	0.70	13.0	1.32	21%	-1.9	507	9.4	55	7	9	2	1	1	07-Nov-89
														08-Nov-89
														09-Nov-89
														10-Nov-89
12.7	0	15.1	0.28	29%	-2.4									11-Nov-89
														12-Nov-89
					0.0	688	27.8	58	9	8	4	6	2	13-Nov-89
				25%										
		GRAND AVG		19%										
		STD DEV:		8%										

ROCK-REED FILTER DATA

SYSTEM TWO (SCIRPUS OR BULRUSH)

	FLOWS (ml/min)			WATER	ORP (mV)		COD		%COD	BOD5		%BOD	COD
DATE	IN	OUT	pH	TEMP(oC)	A	B	mean	std dev	REM'D	mean	std dev	REM'D	/BOD5
26-Aug-89	82	68	7.5	29	-359	-349							
27-Aug-89	82	79	7.3	28.5	-348	-348	77	3.0	15%	18	6.2	35%	4.2
28-Aug-89	80	79		29	-339	-289							
29-Aug-89	79	70	7.5	28	-288	-288	29	2.8	68%	9	2.2	68%	3.2
30-Aug-89	80	74	7.2	29	-269	-279							
31-Aug-89	79	40		29	-269	-289	22	0.0	76%	2	1.0	93%	
01-Sep-89	81	46	7.5	29	-269	-289							
02-Sep-89	82	65	7.4	30	-269	-289	21	5.9	77%	7	0.7	75%	2.9
03-Sep-89	80	55		30	-269	-289	23	3.3	74%	9	0.8	68%	2.5
04-Sep-89	78	40	7.2	29	-279	-289	21	1.6	77%	5	0.1	82%	4.0
	80	62							65%		AVG	70%	3.4
									22.3%		STD	17.7%	
05-Sep-89	82	54	7.4	29	-279	-289							
06-Sep-89	79	44	7.5	28	-308	-318	28	1.5	90%				
07-Sep-89	80	68	7.4	28.5	-308	-308							
08-Sep-89	80	40	7.4	29	-359	-359	85	2.9	71%	30	6.3	77%	2.8
09-Sep-89	81	79	7.4	28.5	-368	-358							
10-Sep-89	80	66	7.3	29	-359	-349	75	4.1	74%				
11-Sep-89	80	46	7.4	28	-348	-338							
12-Sep-89	81	62	7.2	27.5	-368	-358	88	1.4	69%				
13-Sep-89	80	60	7.4	27	-357	-347	68	4.1	76%				
14-Sep-89	80	71	7.2	28.5	-368	-348	109	1.4	62%				
	80	59							74%		AVG	77%	2.8
									8.6%		STD		
15-Sep-89	79	70		25.5	-346	-346							
16-Sep-89	80	64		23.5	-325	-355	103	0.0	71%				
17-Sep-89	80	68		24	-355	-345							
18-Sep-89	79	54		25	-366	-356	103	4.2	71%				
19-Sep-89	77	68		25	-366	-356							
20-Sep-89	81	58		25	-336	-356	94	1.4	74%				
21-Sep-89	79	70		25	-366	-366							
22-Sep-89	79	54		25	-356	-356	85	7.0	76%	37	4.0	72%	2.3
23-Sep-89	80	53		24.5	-366	-366	72	3.3	80%				
24-Sep-89	80	47		23	-355	-355	145	1.5	60%				
	79	61							72%		AVG	72%	2.3
									6.3%		STD		
25-Sep-89	78	70		23	-355	-355							
26-Sep-89	80	76		23	-355	-355	92	2.8	42%				
27-Sep-89	82	78		23	-345	-355							

DATE	FLOWS (ml/min) IN	OUT	pH	WATER TEMP(oC)	ORP (mV) A	B	COD mean	std dev	%COD REM'D	BOD5 mean	std dev	%BOD REM'D	COD /BOD5
28-Sep-89	79	70	7.1	23	-345	-295	62	0.0	61%	28	0.8	66%	2.2
29-Sep-89	80	74		23	-245	-285							
30-Sep-89	80	73	7.4	22.5	-253	-293	51	2.8	68%				
01-Oct-89	80	40	7.8	23	-285	-295							
02-Oct-89	78	60	7.7	24	-295	-285	48	4.7	69%	28	1.2	66%	1.7
03-Oct-89	81	20	7.6	26	-307	-307	39	2.9	75%	27	1.2	67%	1.4
04-Oct-89							84	7.0	47%	22	5.5	73%	3.8
	80	62							60%		AVG	68%	2.3
									12.1%		STD	2.9%	
05-Oct-89	139	118	7.7	25.5	-306	-306							
06-Oct-89	138	131	7.6	25.5	-296	-276	80	2.8	71%				
07-Oct-89	138	80	7.7	26.5	-337	-367							
08-Oct-89	139	80	7.8	25	-346	-376	99	1.4	64%	34	1.1	73%	2.9
09-Oct-89	140	80	7.9	24.5	-385	-405							
10-Oct-89	139	129	7.6	23.5	-405	-405	60	1.4	78%				
11-Oct-89	140	90	7.8	24	-415	-415							
12-Oct-89	138	128	7.7	24	-415	-425	90	1.9	67%				
13-Oct-89	140	95	7.7	25	-416	-436	91	4.2	67%	41	1.9	67%	2.2
14-Oct-89	139	120	7.7	24	-425	-435	107	1.4	61%	49	1.6	61%	2.2
	139	105							68%		AVG	67%	2.4
									5.4%		STD	4.7%	
15-Oct-89	139	120	7.8	24	-415	-435							
16-Oct-89	139	130	7.8	26	-387	-377	62	0.0	38%				
17-Oct-89	141	136	7.6	26.5	-377	-367							
18-Oct-89	139	90	7.8	24	-375	-375	42	4.5	58%				
19-Oct-89	138	120	7.8	22	-384	-374							
20-Oct-89	139	80	7.8	21	-403	-393	34	2.9	66%				
21-Oct-89	140	120	7.6	21	-403	-373							
22-Oct-89	138	124	7.6	22	-404	-374	36	1.4	64%	13	0.8	58%	2.9
23-Oct-89	139	80	7.6	22.5	-364	-374	15	0.0	85%				
24-Oct-89	140	120	7.7	23	-365	-375	29	1.4	71%				
	139	112							64%		AVG	58%	2.9
									14.1%				
25-Oct-89	137	110	7.7	23	-375	-375							
26-Oct-89	140	126	7.8	23	-425	-425	67	1.9	83%				
27-Oct-89	138	90	7.8	22.5	-424	-435							
28-Oct-89			7.7	22	-354	-394	110	3.0	72%				
29-Oct-89	135	90		22.5	-385	-435							
30-Oct-89	135	78		22.5	-424	-444	137	5.7	66%				
31-Oct-89	137	122	6.7	22.5	-344	-404							
01-Nov-89	140	120		22	-414	-434	159	10.8	60%				
02-Nov-89	137	134		22	-404	-424	117	1.4	71%	50	5.7	49%	2.3

DATE	FLOWS (ml/min) IN	OUT	pH	WATER TEMP(oC)	ORP (mV) A	B	COD mean	std dev	%COD REM'D	BOD5 mean	std dev	%BOD REM'D	COD /BOD5
03-Nov-89	138	80		21	-423	-433	115	3.7	71%	48	0	51%	2.4
	137	106							71%		AVG	50%	2.4
									7.1%		STD	1.0%	
04-Nov-89	138	122		21	-433	-433							
05-Nov-89	140	124		21	-433	-423	84	1.9	57%				
06-Nov-89	140	118	7.2	24	-425	-375							
07-Nov-89	140	136	6.9	25	-436	-356	82	1.9	58%	58	2.5	38%	
08-Nov-89	141	140	7.3	25	-436	-436							
09-Nov-89	134	120	7.4	24	-435	-365	62	1.4	68%				
10-Nov-89	138	90	7.4	22	-434	-374							
11-Nov-89	142	94	7.2	21	-433	-393	65	4.2	67%	20	1.4	79%	3.3
12-Nov-89	138	70	7.6	22.5	-444	-434	68	4.2	65%	34	0.5	64%	2.0
13-Nov-89	138	85		23	-425	-375	55	5.0	72%	33	0.9	65%	1.7
	139	110							65%		AVG	61%	2.3
									5.4%		STD	14.8%	
									67%		GRD TOT	65%	2.6
									4.4%		STD DEV	8.2%	0.4

ROCK REED FILTER DATA

SYSTEM TWO (SCIRPUS OR BULRUSH)

TKN		NH4		%TKN	org-N	TS		TVS		TSS		TVSS		
mean	std dev	mean	std dev	REM'D	(mg/l)	mean	std dev	mean	std dev	mean	std dev	mean	std dev	DATE
														26-Aug-89
														27-Aug-89
														28-Aug-89
19.8	0	12.8	0.70		7.0	635.0	56.7	75.0	14.1	27.5	3.5	9.2	3.1	29-Aug-89
														30-Aug-89
														31-Aug-89
														01-Sep-89
12.3	0.17	6.3	0.34	21%	6.0	623.3	23.2	85.0	4.1	18.0	2.0	15.0	1.0	02-Sep-89
														03-Sep-89
11.9	0.22	9.2	1.53	21%	2.7	516.7	163.8	81.7	17.0	26.0	2.8	18.7	2.5	04-Sep-89
				21%										
														05-Sep-89
														06-Sep-89
														07-Sep-89
16.8	0	14.0	0.13	45%	2.8	597	9.4	82	4.7	20	2.8	15	2.5	08-Sep-89
														09-Sep-89
														10-Sep-89
														11-Sep-89
25.7	0.21	25.7	1.17		0.0	4100	703.1	1437	263.4	33	0.9	17	3.8	12-Sep-89
														13-Sep-89
26.0	0.09	25.2	3.38	33%	0.7									14-Sep-89
				39%										
														15-Sep-89
														16-Sep-89
														17-Sep-89
						772	40.3							18-Sep-89
														19-Sep-89
														20-Sep-89
														21-Sep-89
21.5	0.1	28.7	0.21	57%	-7.2									22-Sep-89
														23-Sep-89
34.2	0.8			35%	34.2									24-Sep-89
				46%										
														25-Sep-89
														26-Sep-89
														27-Sep-89

TKN mean	TKN std dev	NH4 mean	NH4 std dev	%TKN REM'D	org-N (mg/l)	TS mean	TS std dev	TVS mean	TVS std dev	TSS mean	TSS std dev	TVSS mean	TVSS std dev	DATE
22.0	0.6	21.7	1.32	15%	0.3	565	7.1	27	6.2	4	2.8	7	1.0	28-Sep-89
														29-Sep-89
														30-Sep-89
														01-Oct-89
					0.0	580	28.6	47	8.5					02-Oct-89
														03-Oct-89
18.8	0.2	14.2	0.58		4.6									04-Oct-89
				15%										
														05-Oct-89
														06-Oct-89
														07-Oct-89
25.5	0.1	20.9	0.51	35%	4.6									08-Oct-89
														09-Oct-89
														10-Oct-89
														11-Oct-89
25.6	0.1			29%	25.6									12-Oct-89
														13-Oct-89
23.1	0.2	25.0	3.64	29%	-1.9									14-Oct-89
				31%										
														15-Oct-89
														16-Oct-89
														17-Oct-89
10.2	0.2	8.6	0.14	15%	1.6									18-Oct-89
														19-Oct-89
														20-Oct-89
														21-Oct-89
8.1	0.2	7.2	0.28	41%	0.9									22-Oct-89
														23-Oct-89
7.1	0.1	6.7	0.14	31%	0.4									24-Oct-89
				29%										
														25-Oct-89
														26-Oct-89
														27-Oct-89
23	0			58%										28-Oct-89
														29-Oct-89
														30-Oct-89
														31-Oct-89
26.3	0.3	31.1	0.14	45%	-4.8									01-Nov-89
														02-Nov-89

TKN		NH4		%TKN	org-N	TS		TVS		TSS		TVSS		
mean	std dev	mean	std dev	REM'D	(mg/l)	mean	std dev	mean	std dev	mean	std dev	mean	std dev	DATE
32.3	0.2	32.9	2.29	14%	-0.6									03-Nov-89
				39%										
														04-Nov-89
														05-Nov-89
														06-Nov-89
10.3	0.14	12.1	0.00	34%	-1.8	468	59	28	5	5	2	5	1	07-Nov-89
														08-Nov-89
														09-Nov-89
														10-Nov-89
12.1	0	14.6	0.09	39%	-2.5									11-Nov-89
														12-Nov-89
		7.4	0.45		-7.4	993	21	98	9	11	2	1	1	13-Nov-89
				36%										
			GRAND AVG	32%										
			STD DEV:	10%										

ROCK-REED FILTER DATA

SYSTEM THREE (CONTROL)

DATE	FLOWS (ml/min) IN	OUT	pH	WATER TEMP(oC)	ORP (mV) A	B	COD mean	std dev	%COD REM'D	BOD5 mean	std dev	%BOD REM'D	COD /BOD5
26-Aug-89	80	80	7.6	29	-359	-369							
27-Aug-89	85	85	7.4	29	-299	-369	119.7	1.6		41	7		2.9
28-Aug-89	83	79	7.5	29.5	-299	-319							
29-Aug-89	80	72	7.7	28	-268	-278	70.3	3.3	3%	20	0.9	10%	3.5
30-Aug-89	80	78	7.6	29	-279	-279							
31-Aug-89	79	72	7.7	31	-280	-290	39.3	2.9	46%				
01-Sep-89	79	74	7.6	30.5	-290	-280							
02-Sep-89	84	81		30	-279	-279	38.5	8.5	47%	22	1.1	5%	1.8
03-Sep-89	80	78		30	-279	-279	36.3	3.3	50%	16	1.4	30%	2.3
04-Sep-89	81	80	7.7	30	-289	-289	39.2	1.6	46%	15	0.5	33%	2.6
AVG	81	78							38%		AVG	20%	2.6
									17.7%		STD	12.3%	
05-Sep-89	82	85	7.7	29.5	-289	-289							
06-Sep-89	80	80	7.7	29	-369	-369	70.8	2.9	67%	27	3.2	73%	2.7
07-Sep-89	81	78	7.7	29	-369	-369							
08-Sep-89	82	80	7.6	29	-369	-369	130.0	4.2	40%				
09-Sep-89	81	77		28.5	-358	-378							
10-Sep-89	82	76	7.4	29	-349	-369	135.7	7.9	37%				
11-Sep-89	79	80	7.6	29	-359	-369							
12-Sep-89	83	83	7.4	27.5	-358	-368	130.4	1.4	40%	54	1.5	46%	2.4
13-Sep-89	80	86	7.5	28	-348	-368	113.0	1.4	48%				
14-Sep-89	79	71	7.5	28.5	-358	-368	161.0	2.8	25%				
AVG	81	80							43%		AVG	60%	2.5
									12.7%		STD	13.5%	
15-Sep-89	79	80		25	-346	-356							
16-Sep-89	81.5	78		23.5	-365	-365	134.0	1.4	54%				
17-Sep-89	80	75		25.5	-356	-366							
18-Sep-89	80	70		25	-356	-366	137.7	2.9	52%	72	1.4	33%	1.9
19-Sep-89	80	79		25	-366	-366							
20-Sep-89	81	82		25	-306	-366	131.5	1.5	54%				
21-Sep-89	82	82		25	-376	-366							
22-Sep-89	80	70		25	-346	-366	128.0	7.0	56%	54	0	50%	2.4
23-Sep-89	81	68		24.5	-376	-366	124.3	4.2	57%				
24-Sep-89	80.5	80		24	-355	-365	148.3	3.3	49%				
AVG	81	76							54%		AVG	41%	2.1
									2.7%		STD	8.4%	
25-Sep-89	79	78		23	-355	-365							
26-Sep-89	79	70		23	-365	-365	113.5	1.5	11%				
27-Sep-89	81	77		23	-315	-355							

DATE	FLOWS (ml/min) IN	OUT	pH	WATER TEMP(oC)	ORP (mV) A	B	COD mean	std dev	%COD REM'D	BOD5 mean	std dev	%BOD REM'D	COD /BOD5
28-Sep-89	80	74	7.3	23	-345	-315	73.0	2.8	43%	45	6.4	32%	1.6
29-Sep-89	79	90		23	-315	-295							
30-Sep-89	81	76	7.9	22	-344	-294	71.0	0.0	44%				
01-Oct-89	82	100	7.9	24	-355	-295							
02-Oct-89	80	76	7.9	24	-345	-305	84.0	4.5	34%	37	2.4	44%	2.3
03-Oct-89							83.0	1.4	35%	42	0.5	36%	2.0
04-Oct-89	81	60	7.8	27	-367	-307	108.0	2.8	15%				
AVG	80	78							30%		AVG	38%	2.0
									12.9%		STD	5.0%	
05-Oct-89	138	120	7.9	25	-366	-306							
06-Oct-89	140	138	7.6	25	-346	-366	98.0	1.4	54%				
07-Oct-89	139	140	7.8	27	-387	-377							
08-Oct-89	137	140	7.7	25	-386	-386	110.0	2.4	48%	36	3.8	62%	3.0
09-Oct-89	136	140	7.8	24	-415	-405							
10-Oct-89	140	130	7.7	23	-445	-415	47.0	2.8	78%				
11-Oct-89	138	144	7.7	24	-415	-415							
12-Oct-89	140	144	7.7	23.5	-445	-425	111.0	1.4	48%	51		47%	2.2
13-Oct-89	140	138	7.8	25	-456	-436	100.0	2.4	53%				
14-Oct-89	140	130	7.8	24	-465	-435	98.0	1.4	54%	39	1.2	59%	2.5
AVG	139	136							56%		AVG	56%	2.6
									10.2%		STD	6.6%	
15-Oct-89	140	130	7.8	24	-445	-435							
16-Oct-89	139	130	7.9	26	-437	-427	59.3	9.4	32%				
17-Oct-89	140	136	7.9	26	-437	-387							
18-Oct-89	139	110	8.1	23	-415	-395	45.7	4.6	47%				
19-Oct-89	141	130	7.7	22	-424	-424							
20-Oct-89	140	124	7.9	21	-413	-433	25.7	3.3	70%				
21-Oct-89	139	134	7.8	21	-413	-443							
22-Oct-89	141	138	7.8	22	-414	-444	48.0	1.4	60%	16	1.4	39%	3.1
23-Oct-89	138	130	7.9	23	-425	-435	32.7	6.5	62%				
24-Oct-89	139	136	7.8	23	-425	-435	44.0	1.4	49%				
AVG	140	130							53%		AVG	39%	2.3
									12.5%		STD		
25-Oct-89	140	130	7.9	22	-414	-424							
26-Oct-89	139	136	7.8	22.5	-454	-444	93.0	1.4	72%				
27-Oct-89	141	132	7.8	21	-463	-443							
28-Oct-89			7.7	22	-454	-434	122.0	1.4	63%				
29-Oct-89	139	132		22	-464	-434							
30-Oct-89	135	124		23	-455	-435	123.3	2.9	62%				
31-Oct-89	137	132	6.5	22.5	-454	-434							
01-Nov-89	137	128		22	-444	-424	126.3	5.0	61%				
02-Nov-89	139	132		22	-444	-424	106.3	1.9	67%	28	1.6	65%	3.9

03-Nov-89	139	124		21	-443	-403	81.0	3.7	75%	37	2.5	53%	2.2
AVG	138	130							67%		AVG	59%	3.0
									5.2%		STD	5.8%	
04-Nov-89	1.9	134		24	-453	-433							
05-Nov-89	138	132		21	-433	-433	93.7	1.9	41%				
06-Nov-89	141	140	7.3	24	-455	-435							
07-Nov-89	140	138	7.1	25	-466	-426	82.3	1.9	48%	48	2.5	36%	1.7
08-Nov-89	140	130	7.4	24	-466	-446							
09-Nov-89	139	116	7.7	23.5	-455	-405	68.0	1.4	57%				
10-Nov-89	138	114	7.5	22	-444	-404							
11-Nov-89	140	98	7.3	21	-463	-403	87.0	3.7	45%	27	0.8	64%	3.2
12-Nov-89	136	110	7.5	22	-454	-444	108.0	1.4	31%	39	0.5	48%	2.7
13-Nov-89	140	121		22	-465	-415	69.0	2.0	56%	36	1.2	52%	1.9
	125	123							46%		AVG	50%	2.4
									8.8%		STD	10.1%	
									48%		GRD TOT	45%	2.4
									10.6%		STD DEV	12.8%	0.3

ROCK REED FILTER DATA

SYSTEM THREE (CONTROL)

TKN		NH4		%TKN	org-N	TS		TVS		TSS		TVSS		
mean	std dev	mean	std dev	REM'D	(mg/l)	mean	std dev	mean	std dev	mean	std dev	mean	std dev	DATE
														26-Aug-89
														27-Aug-89
														28-Aug-89
16.7	0.05	5.5	0.09		11.2	430.0	79.7	45.0	8.2	12.5	3.5	1.7	1.2	29-Aug-89
														30-Aug-89
														31-Aug-89
														01-Sep-89
13.2	0.14	5.5	0.09		7.7	463.3	23.9	71.7	10.3	27.0	3.0	13.0	3.0	02-Sep-89
														03-Sep-89
11.9	0.22	13.9	0.86	1%	-2.0	425.0	76.3	55.0	10.8	36.0	4.3	26.0	3.3	04-Sep-89
				1%										
														05-Sep-89
														06-Sep-89
														07-Sep-89
26.6	1.40	18.6	0.32		8.0	525	20.4	128	19.3					08-Sep-89
														09-Sep-89
														10-Sep-89
														11-Sep-89
29.6	0.38	21.3	1.53		8.3	4388	571.9	1578	98.0	36	2.8	20	0	12-Sep-89
														13-Sep-89
28.4	0.00	15.2	0.78	2%	13.2									14-Sep-89
				2%										
														15-Sep-89
														16-Sep-89
														17-Sep-89
						488	120.4							18-Sep-89
														19-Sep-89
														20-Sep-89
														21-Sep-89
33.9	0.4	29.3	0.14	15%	4.6									22-Sep-89
														23-Sep-89
35.5	0.6			16%	35.5									24-Sep-89
				16%										
														25-Sep-89
														26-Sep-89
														27-Sep-89

TKN mean	TKN std dev	NH4 mean	NH4 std dev	%TKN REM'D	org-N (mg/l)	TS mean	TS std dev	TVS mean	TVS std dev	TSS mean	TSS std dev	TVSS mean	TVSS std dev	DATE
23.4	0.3	21.0	0.14	-13%	2.4	513	11.8	50	7.1	5	1.4	4.5	1.5	28-Sep-89
														29-Sep-89
														30-Sep-89
														01-Oct-89
						468	20.5	17	6.2					02-Oct-89
														03-Oct-89
19.5	0.1	12.1	0.34	-42%	7.4									04-Oct-89
				-27%										
														05-Oct-89
														01-Jan-00
30.6	0.0	8.5	0.51		22.1									02-Jan-00
														03-Jan-00
														04-Jan-00
														05-Jan-00
27.4	0.4			1%	27.4									06-Jan-00
														07-Jan-00
24.2	0.4	22.6	0.14	3%	1.6									08-Jan-00
				2%										
														15-Oct-89
														16-Oct-89
														17-Oct-89
12.9	0.1	8.2	0.00	-32%	4.7									18-Oct-89
														19-Oct-89
														20-Oct-89
														21-Oct-89
2.8	0.0	8.7	0.28	77%	-5.9									22-Oct-89
														23-Oct-89
9.3	0.5	8.9	0.21	-5%	0.5									24-Oct-89
				13%										
														25-Oct-89
														26-Oct-89
														27-Oct-89
24.6	0	27.4	0.14	45%	-2.8									28-Oct-89
														29-Oct-89
														30-Oct-89
														31-Oct-89
29.3	0.1	31.9	0.48	26%	-2.6									01-Nov-89
														02-Nov-89

32.1	0.1	34.8	1.32	-5%	-2.7									03-Nov-89
				22%										
														04-Nov-89
														05-Nov-89
														06-Nov-89
11.7	0.14	14.0	1.32	33%	-2.3	397	26	25	11	8	3	2	2	07-Nov-89
														08-Nov-89
														09-Nov-89
														10-Nov-89
14.1	0.42	15.6	0.24	11%	-1.5									11-Nov-89
														12-Nov-89
		11.4	0.14			893	29	58	5	9	4			13-Nov-89
				22%										
			GRAND AVG	6%										
			STD DEV:	15%										

APPENDIX B

Computer Program Listing for Simulations and Data from the Denham Springs Rock-Plant Filter

COMPUTER MODEL FOR BENCH-SCALE SYSTEMS

```
{This program uses a datafile containing daily climatic,
influent flow data, and BOD5 analyses and predicts
the effluent BOD5 concentration}


CONST
     PI       = 3.1415927;
     dt       = 1;              {DAY}
     Limit    = 79;             {DAYS}

VAR
   today, day1, day2, num_rcks, air_tmp_oF_1,
air_tmp_oF_2, wt_tmp_oC_1, wt_tmp_oC_2, COD_in1, COD_in2,
COD_out1, COD_out2, Nin1, Nin2, Nout1, Nout2, ppn1, ppn2,
Run, PARAM, observs                                 :INTEGER;

ASC, BETWEEN
                                                    :BOOLEAN;

titleline
                                                    :STRING[80];


day, HDay, rck_dpth, init_por, length, width, sys_wat_vol,
outlet_dpth, surf_area, avg_rck_size, rck_surf_area, lat,
HQ_in, H_air_tmp_oF, BOD5_in1, BOD5_in2, BOD5_out1,
BOD5_out2, Hdecl, decl1, decl2, Hppn, wat_dpth, D_S_L,
D_S_M, D_R_M, L_R_M, L_S_M, sol_radn_inch, Q_in1, Q_in2,
meas_Q_out1, meas_Q_out2, live_sht_mass, dead_sht_mass,
rt_to_sht, live_rt_mass, dead_rt_mass, litterfall_rate,
percent_harvest, sht_decay_rate, rt_death_rate,
rt_decay_rate, dy_SpgEqunx1, dy_SpgEqunx2, air_tmp_oC_1,
air_tmp_oC_2, H_air_tmp_oC, sol_hlf_dy1, sol_hlf_dy2,
H_sol_hlf_dy, net_prodn, tot_rt_mass, dead_shts_lft,
C_in1, C_in2, C_out1, C_out2, Q_in, ppn, air_tmp_oF,
air_tmp_oC, decl, wt_tmp_oC, C_in, N_in, sol_hlf_dy,
H_wt_tmp_oC, HC_in, HNin, C_per_plant, C_assln_rate_20,
C_sys_mass, C_assln_rate, C_assld, C_out, plt_decay_C,
C_sys, calc_C_out, calc_BOD_out, perct_BOD_remd,
rck_bug_mass, rt_bug_mass, rt_surf_area, rt_dnsty,
RkBugGrwth20, RkBugGrwth, RtBugGrwth20, RtBugGrwth,
meas_Q_out, C_sttld, C_settle_frac, HmeasQ_out, SR_BOD,
SSR_BOD, SSR_PARAM_HI, SSR_PARAM_LO, LO_PARAM, HI_PARAM,
STEP, LR, SDR, RDthR, RDcyR, RD, DCC, SCP, SDsR, RkBG,
RtBG, SSF, IP, RAV, rt_area_to_vol, alpha, lambda, nu,
psi, ro, Q_out, CSC, C_sys_conc, DRtM, HoldDRM, CHISQ,
CHISQRD, CSM_hold, SSRobs
                                                    : REAL;

litterfall, NP, DSL, DSM, DRM, LRM, LSM, Csys
```

```
                                    : ARRAY[1..4] OF REAL;

Datafile, Outfile
                                              : TEXT;


PROCEDURE Initialize;
BEGIN
     ASSIGN(Datafile, 'rslt\BSData2.pas');
     RESET(Datafile);
     ASSIGN(Outfile, 'rslt\BSOut2.pas');
     REWRITE(Outfile);
     READLN(Datafile);
     READLN(Datafile);
     READLN(Datafile);
     READLN(Datafile);
     READLN(Datafile);
     WRITELN(Outfile, ' ':24, '       SCIRPUS DATA SET');
     WRITELN(Outfile, ' ':24, '         Effluent BOD');
     WRITELN(Outfile);
     WRITELN(Outfile);
     WRITELN(Outfile, ' ':24, '         meas''d
calc''d');
     WRITELN(Outfile, ' ':24, 'Day      BOD outd      BOD
out');
     WRITELN(Outfile, ' ':24,
'______________________________');
     WRITELN(Outfile);
END;

PROCEDURE AssignPhyslParameters;
BEGIN
     today        := 0;
     observs      := 0;
     rck_dpth     := 2;                    {ft}
     init_por     := 0.5;
     length       := 5;                    {ft}
     width        := 1.5;                  {ft}
     wat_dpth     := 1.7;
     sys_wat_vol  := wat_dpth * length * width * init_por;
    {cu ft}
     outlet_dpth  := 1.5;                  {ft}
     surf_area    := length * width;         {sq ft}
     avg_rck_size := SQRT(1 * 3)/12;         {ft}
     num_rcks     := ROUND((1-init_por) * rck_dpth *
surf_area/(PI * (EXP(3 *
                         LN(avg_rck_size)))/6));
     rck_surf_area:= num_rcks * PI * SQR(avg_rck_size);
{sq ft}
     rck_bug_mass := rck_surf_area * SQR(30.48) * EXP(-4 *
LN(10)); {mg}
     lat          := (29+56/60+53/3600) * PI/180;
```

```
END;


PROCEDURE AssignPlantParameters;
BEGIN
     live_sht_mass   := 3000; {3000 gms, measured in BS
study}
     dead_sht_mass   := 0;    {0 gms, due to 100% harvest}
     rt_to_sht       := 1;    {1; from Kadlec & Hammer,
1988}
     live_rt_mass    := live_sht_mass * rt_to_sht;
     dead_rt_mass    := 2000; {MUST CALIBRATE}
     litterfall_rate := 0.2;  {0.2/day; K & H, 1988 * 10}
     percent_harvest := 100;
     sht_decay_rate  := 0.004; {0.004/day; K & H, 1988 *
10}
     rt_death_rate   := 0.00001; {MUST CALIBRATE}
     rt_decay_rate   := 0.004; {0.004 1/day; K & H, 1988 *
10}
     dead_shts_lft   := 0;
     rt_dnsty        := 0.7;  {MUST CALIBRATE}
     rt_area_to_vol  := 8;    {80; based on 0.05 cm diam
cylindrical root... then assuming only 1/10 produces much
oxygen}
     alpha           := -0.00034; {-0.00034 m^2/g; Morris,
1984}
     lambda          := 33;       {33 mW/cm^2; Morris,
1984}
     nu              := 0.36;     {0.36% dry wt; Morris,
1984}
     psi             := 0.00071;  {0.00071/oC/hr; Morris,
1984}
     ro              := 0.000023; {0.000023/oC/hr; Morris,
1984}
END;


PROCEDURE AssignCarbonParameters;
BEGIN
     C_per_plant      := 429; {429 mg/g; Morris, Houghton,
and Botkin, 1984, Ecol'l Modelling, v26, pp155-175}
     C_sys_mass       := 20 * 28.315585 * sys_wat_vol;
{mg}
     RkBugGrwth20     := 0.03; {MUST CALIBRATE}
     RtBugGrwth20     := 0.2;  {MUST CALIBRATE}
     C_settle_frac    := 0.5;  {MUST CALIBRATE}
     SSR_BOD          := 0;
     CHISQRD          := 0;
END;


PROCEDURE ReadData;
```

```
BEGIN
     IF today=0 THEN
     BEGIN
          READLN(Datafile, day1, Q_in1, meas_Q_out1,
air_tmp_oF_1, wt_tmp_oC_1, COD_in1, Nin1, COD_out1, Nout1,
ppn1, decl1, dy_SpgEqunx1);
          READLN(Datafile, day2, Q_in2, meas_Q_out2,
air_tmp_oF_2, wt_tmp_oC_2, COD_in2, Nin2, COD_out2, Nout2,
ppn2, decl2, dy_SpgEqunx2);
          decl1              := decl1/180 * PI;
          decl2              := decl2/180 * PI;
          air_tmp_oC_1       := (air_tmp_oF_1 - 32)/9 * 5;
          air_tmp_oC_2       := (air_tmp_oF_2 - 32)/9 * 5;
          sol_hlf_dy1        := (122.142857 - dy_SpgEqunx1/3)
* PI/180;
          sol_hlf_dy2        := (122.142857 - dy_SpgEqunx2/3)
* PI/180;
          BOD5_in1           := COD_in1/2.7;
          BOD5_in2           := COD_in2/2.7;
          BOD5_out1          := COD_out1/2.7;
          BOD5_out2          := COD_out2/2.7;
          C_in1              := BOD5_in1/0.65625; {Metcalf &
Eddy}
          C_in2              := BOD5_in2/0.65625;
          C_out1             := BOD5_out1/0.65625;
{Metcalf & Eddy}
          C_out2             := BOD5_out2/0.65625;
          Q_in1              := Q_in1 * 1.44/28.315585; {cfd}
          meas_Q_out1        := meas_Q_out1 * 1.44/28.315585;
    {cfd}
          Q_in2              := Q_in2 * 1.44/28.315585;
   {cfd}
          meas_Q_out2        := meas_Q_out2 * 1.44/28.315585;
{cfd}
          today              := today + 1;
     END ELSE
     BEGIN
        day1           :=  day2;
        Q_in1          :=  Q_in2;
        meas_Q_out1    :=  meas_Q_out2;
        air_tmp_oF_1   :=  air_tmp_oF_2;
        air_tmp_oC_1   :=  air_tmp_oC_2;
        wt_tmp_oC_1    :=  wt_tmp_oC_2;
        COD_in1        :=  COD_in2;
        Nin1           :=  Nin2;
        COD_out1       :=  COD_out2;
        Nout1          :=  Nout2;
        decl1          :=  decl2;
        ppn1           :=  ppn2;
        dy_SpgEqunx1   :=  dy_SpgEqunx2;
        sol_hlf_dy1    :=  sol_hlf_dy2;
        BOD5_in1          := BOD5_in2;
```

```
        BOD5_out1           := BOD5_out2;
        C_in1               := C_in2;
        C_out1              := C_out2;
        READLN(Datafile, day2, Q_in2, meas_Q_out2,
air_tmp_oF_2, wt_tmp_oC_2, COD_in2, Nin2, COD_out2, Nout2,
ppn2, decl2, dy_SpgEqunx2);
        decl2               := decl2/180 * PI;
        air_tmp_oC_2        := (air_tmp_oF_2 - 32)/9 * 5;
        sol_hlf_dy2         := (122.142857 - dy_SpgEqunx2/3) *
PI/180;
        BOD5_in2            := COD_in2/2.7;
        BOD5_out2           := COD_out2/2.7;
        C_in2               := BOD5_in2/0.65625;
        C_out2              := BOD5_out2/0.65625;
        Q_in2               := Q_in2 * 1.44/28.315585; {cfd}
        meas_Q_out2         := meas_Q_out2 * 1.44/28.315585;
  {cfd}
        today               := today + 1;
        END;
END;


PROCEDURE CalcCarbonParameters;
BEGIN
     C_in          := (C_in * Q_in * 28.315585) * dt;  {mg}
     IF C_sys_mass > 0 THEN
     BEGIN
          C_out    := (C_sys_mass/sys_wat_vol * meas_Q_out)
* dt;  {mg}
          C_sttld := (C_sys_mass * C_settle_frac) * dt;
     {mg}
     END ELSE
     BEGIN
          C_out    := 0;
          C_sttld := 0;
     END;
     plt_decay_C  := (C_per_plant * (sht_decay_rate *
dead_sht_mass + rt_decay_rate * dead_rt_mass)) * dt;
END;


FUNCTION sol_radn_mWcc(time, decl, sol_hlf_dy: REAL):
REAL;

VAR
   rad_decl, sol_dist_ratio, N
        :REAL;

BEGIN
     rad_decl:= decl/180 * PI;
     sol_dist_ratio := 0.9942632+(0.000316 * time);
     sol_radn_mWcc  := 0.56 * 1440/PI * 139.5 *
```

```
sol_dist_ratio * ((PI/2 * SIN(lat) *
SIN(rad_decl))+(COS(lat) *  COS(rad_decl) *
SIN(sol_hlf_dy)));
     N               := 0.56 * 1440/PI * 139.5 *
sol_dist_ratio * ((PI/2 * SIN(lat) *
SIN(rad_decl))+(COS(lat) * COS(rad_decl) *
SIN(sol_hlf_dy)));
END;


FUNCTION SunAngle(decl: REAL) :REAL;
{This function involves finding the arc cosine, in
radians,  of "B", as
directed on pgs 8 & 9 of "Pascal Programs for Scientists
and Engineers"}

VAR
   A, B, C, M
         :REAL;

BEGIN
     B := -SIN(decl)/COS(lat);
     IF B=0.0 THEN SunAngle := PI/2
     ELSE
         IF B=1.0 THEN SunAngle := 0.0
         ELSE
             IF B=-1.0 THEN SunAngle := PI
             ELSE
                 BEGIN
                      C := B/SQRT(1.0 - SQR(B));
                      A := ARCTAN(ABS(1/C));
                      IF C>0.0 THEN
                         BEGIN
                              SunAngle := A;
                         END
                      ELSE
                          BEGIN
                               SunAngle := PI - A;
                               M        := PI - A;
                          END;
                 END;
END;


PROCEDURE CalcRunges;

VAR
   gp, resp
         :REAL;

BEGIN
     CalcCarbonParameters;
```

```
     gp            := psi * air_tmp_oC * 4 *
SIN(SunAngle(decl)) *
(LN(sol_radn_mWcc(day, decl, sol_hlf_dy) * EXP(alpha *
(live_sht_mass/(surf_area*SQR(0.3048)))/
SIN(SunAngle(decl))) + lambda) -
LN(sol_radn_mWcc(day, decl, sol_hlf_dy) + lambda))/ (alpha
* (4 + nu)) * 24 * SQR(0.3048)*surf_area;      {g/day}

     resp          := (ro * air_tmp_oC*(1+rt_to_sht) *
(live_sht_mass/(surf_area*SQR(0.3048))))* 24 * SQR(0.3048)
* surf_area;      {g/day}

     NP[Run]          := gp - resp;
     IF (live_sht_mass > 0) THEN
        DSL[Run]      := ((litterfall_rate * live_sht_mass)
- (percent_harvest/100/dt * dead_sht_mass)) * dt  {gms}
     ELSE DSL[Run]    := 0;
     DSM[Run]         := dead_shts_lft - (sht_decay_rate *
dead_shts_lft * dt);   {gms}
     IF live_rt_mass > 0 THEN
        DRM[Run]      := (rt_death_rate * live_rt_mass -
            rt_decay_rate * dead_rt_mass) * dt  {gms}
     ELSE DRM[Run]    := 0;
     LRM[Run]         := ((rt_to_sht/(1+rt_to_sht)) *
NP[Run] - live_rt_mass *  rt_death_rate) * dt;  {gms}
     rt_surf_area     := LRM[Run]/ rt_dnsty *
rt_area_to_vol {sq area/cu vol}; {sq cm}
     rt_bug_mass      := EXP(5 * LN(10)) * rt_surf_area *
EXP(-9 * LN(10)); {mg} {a hundred thous bugs/ sq cm - Dr
Ralph; one billionth mg per bug - Handbook}
     IF C_sys_mass > 0 THEN
     BEGIN
          RkBugGrwth := RkBugGrwth20 * EXP((wt_tmp_oC -
20) * LN(1.047));
          RtBugGrwth := RtBugGrwth20 * EXP((wt_tmp_oC -
20) * LN(1.047));
          C_assld   := (RkBugGrwth * rck_bug_mass +
RtBugGrwth * rt_bug_mass) * C_sys_mass * dt; {mg}
     END
     ELSE C_assld   := 0;
     LSM[Run]         := ((1/(1+rt_to_sht)) * NP[Run] -
litterfall_rate * live_sht_mass) * dt;    {gms}
     litterfall[Run] := litterfall_rate * live_sht_mass;
{gms/day}
     Csys[Run]        := C_in + plt_decay_C - C_sttld -
C_assld - C_out; {mg}
END;


PROCEDURE Rungematic;
BEGIN
     Run          := 1;
```

```
L_S_M          := live_sht_mass;
D_S_L          := dead_shts_lft;
D_S_M          := dead_sht_mass;
D_R_M          := dead_rt_mass;
L_R_M          := live_rt_mass;
C_sys          := C_sys_mass;
HDay           := (Day1 + Day2)/2;
HQ_in          := (Q_in1 + Q_in2)/2;
HmeasQ_out     := (meas_Q_out1 + meas_Q_out2)/2;
Hppn           := (ppn1 + ppn2)/2;
H_air_tmp_oF := (air_tmp_oF_1 + air_tmp_oF_2)/2;
H_air_tmp_oC := (air_tmp_oC_1 + air_tmp_oC_2)/2;
H_wt_tmp_oC  := (wt_tmp_oC_1 + wt_tmp_oC_2)/2;
H_sol_hlf_dy := (sol_hlf_dy1 + sol_hlf_dy2)/2;
Hdecl          := (decl1 + decl2)/2;
HC_in          := (C_in1 + C_in2)/2;
HNin         := (Nin1 + Nin2)/2;
FOR Run:=1 TO 4 DO
BEGIN
     IF Run=1 THEN
     BEGIN
          day          := day1;
          Q_in         := Q_in1;
          meas_Q_out   := meas_Q_out1;
          air_tmp_oC   := air_tmp_oC_1;
          air_tmp_oF   := air_tmp_oF_1;
          wt_tmp_oC    := wt_tmp_oC_1;
          C_in         := C_in1;
          N_in         := Nin1;
          ppn          := ppn1;
          decl         := decl1;
          sol_hlf_dy   := sol_hlf_dy1;
          CalcRunges;
          live_sht_mass:= live_sht_mass + LSM[Run]/2;
          dead_shts_lft:= dead_shts_lft + DSL[Run]/2;
          dead_sht_mass:= dead_sht_mass + DSM[Run]/2;
          dead_rt_mass := dead_rt_mass  + DRM[Run]/2;
          live_rt_mass := live_rt_mass  + LSM[Run]/2;
          C_sys_mass   := C_sys_mass    +
Csys[Run]/2;
     END
     ELSE IF Run=2 THEN
     BEGIN
          day          := Hday;
          Q_in         := HQ_in;
          meas_Q_out   := HmeasQ_out;
          air_tmp_oC   := H_air_tmp_oC;
          air_tmp_oF   := H_air_tmp_oF;
          wt_tmp_oC    := H_wt_tmp_oC;
          C_in         := HC_in;
          N_in         := HNin;
          ppn          := Hppn;
```

```
                decl          := Hdecl;
                sol_hlf_dy    := H_sol_hlf_dy;
                CalcRunges;
                live_sht_mass:= live_sht_mass + LSM[Run]/2;
                dead_shts_lft:= dead_shts_lft + DSL[Run]/2;
                dead_sht_mass:= dead_sht_mass + DSM[Run]/2;
                dead_rt_mass := dead_rt_mass  + DRM[Run]/2;
                live_rt_mass := live_rt_mass  + LSM[Run]/2;
                C_sys_mass   := C_sys_mass    +
Csys[Run]/2;
           END
           ELSE IF Run=3 THEN
           BEGIN
                day           := Hday;
                Q_in          := HQ_in;
                meas_Q_out    := HmeasQ_out;
                air_tmp_oC    := H_air_tmp_oC;
                air_tmp_oF    := H_air_tmp_oF;
                wt_tmp_oC     := H_wt_tmp_oC;
                C_in          := HC_in;
                N_in          := HNin;
                ppn           := Hppn;
                decl          := Hdecl;
                sol_hlf_dy    := H_sol_hlf_dy;
                CalcRunges;
                live_sht_mass:= live_sht_mass + LSM[Run];
                dead_shts_lft:= dead_shts_lft + DSL[Run];
                dead_sht_mass:= dead_sht_mass + DSM[Run];
                dead_rt_mass := dead_rt_mass  + DRM[Run];
                live_rt_mass := live_rt_mass  + LSM[Run];
                C_sys_mass   := C_sys_mass    + Csys[Run];
           END
           ELSE IF Run=4 THEN
           BEGIN
                day           := day2;
                Q_in          := Q_in2;
                meas_Q_out    := meas_Q_out2;
                air_tmp_oC    := air_tmp_oC_2;
                air_tmp_oF    := air_tmp_oF_2;
                wt_tmp_oC     := wt_tmp_oC_2;
                C_in          := C_in2;
                N_in          := Nin2;
                ppn           := ppn2;
                decl          := decl2;
                sol_hlf_dy    := sol_hlf_dy2;
                CalcRunges;
           END;
      END;
      net_prodn     := (NP[1] + 2 * NP[2] + 2 *  NP[3] +
NP[4])/6;
      live_sht_mass:= L_S_M + (LSM[1] + 2 * LSM[2] + 2 *
LSM[3] + LSM[4])/6;
```

```
     dead_shts_lft:= D_S_L + (DSL[1] + 2 * DSL[2] + 2 *
DSL[3] + DSL[4])/6;
     dead_sht_mass:= D_S_M + (DSM[1] + 2 * DSM[2] + 2 *
DSM[3] + DSM[4])/6;
     dead_rt_mass := D_R_M + (DRM[1] + 2 * DRM[2] + 2 *
DRM[3] + DRM[4])/6;
     live_rt_mass := L_R_M + (LRM[1] + 2 * LRM[2] + 2 *
LRM[3] + LRM[4])/6;
     tot_rt_mass  := dead_rt_mass + live_rt_mass; {gms}
     C_sys_mass   := C_sys + (Csys[1] + 2 * Csys[2] +
                     2 * Csys[3] + Csys[4])/6;
     calc_C_out   := C_sys_mass/sys_wat_vol/28.315585;
{mg/l}
     calc_BOD_out := calc_C_out * 0.65625;
     perct_BOD_remd := (BOD5_in1 - calc_BOD_out)/ BOD5_in1
* 100;
     IF BOD5_out2 <> 0 THEN
     BEGIN
          observs  := observs + 1;
          SR_BOD   := SQR(BOD5_out2 - calc_BOD_out);
          SSR_BOD  := SSR_BOD + SR_BOD;
          CHISQ    := SQR(BOD5_out2 -
calc_BOD_out)/calc_BOD_out;
          CHISQRD  := CHISQRD + CHISQ;
          WRITELN(Outfile, ' ':25, day2:2, ' ':7,
BOD5_out2:5:1, ' ':7, calc_BOD_out:5:1);
     END;
END;


PROCEDURE InitializeAssign;
BEGIN
     Initialize;
     AssignPhyslParameters;
     AssignPlantParameters;
     AssignCarbonParameters;
END;


PROCEDURE DoIt;
BEGIN
     WHILE today < Limit DO
     BEGIN
          ReadData;
          Rungematic;
     END;
END;


PROCEDURE GradientSearch;
BEGIN
     CLRSCR;
```

```
     WRITELN(' ':17, 'GRADIENT SEARCH PARAMETER
OPTIMIZATION METHOD');
     WRITELN(' ':17, '          Scirpus System Data');
     WRITELN(' ':7, 'Parameter', ' ':7, 'Param Value', '
':7, 'SSR BOD/obs',
               ' ':3, '# obs', ' ':3, 'Chi Sqrd');
     WRITELN(' ':5,
'__________________________________________________________
_________');
     FOR PARAM := 9 TO 10 DO
     BEGIN
          IF PARAM=1 THEN
             BEGIN
{                         DoIt;
                         SSR_BOD := SSR_BOD/observs;
                         WRITELN(' ':5, 'Rt Death Rate', '
':8, rt_death_rate:5:5, ' ':11, SSR_BOD:6:0, ' ':7,
observs:2, ' ':6, CHISQRD:6:0);
                         CLOSE(Datafile);
                         InitializeAssign;
                         rt_death_rate := rt_death_rate -
0.000005;
                         DoIt;
                         SSR_BOD := SSR_BOD/observs;
                         WRITELN(' ':26, rt_death_rate:5:5,
' ':11,SSR_BOD:6:0, ' ':7, observs:2, ' ':6, CHISQRD:6:0);
                        CLOSE(Datafile);
                         InitializeAssign;
                         rt_death_rate := rt_death_rate +
0.000005;
                         DoIt;
                         SSR_BOD := SSR_BOD/observs;
                         WRITELN(' ':26, rt_death_rate:5:5,
' ':11,SSR_BOD:6:0, ' ':7, observs:2, ' ':6, CHISQRD:6:0);
                         WRITELN;
                         CLOSE(Datafile);
                         CLOSE(Outfile);}
             END ELSE IF PARAM=2 THEN
                 BEGIN
{                         InitializeAssign;
                         rt_dnsty := rt_dnsty - 0.2;
                         DoIt;
                         SSR_BOD := SSR_BOD/observs;
                         WRITELN(' ':5, 'Rt Density', '
':11, rt_dnsty:5:4, ' ':12, SSR_BOD:6:0, ' ':7, observs:2,
' ':6, CHISQRD:6:0);
                         CLOSE(Datafile);
                         InitializeAssign;
                         rt_dnsty := rt_dnsty + 0.2;
                         DoIt;
                         SSR_BOD := SSR_BOD/observs;
                         WRITELN(' ':26, rt_dnsty:5:4, '
```

```
':12, SSR_BOD:6:0, ' ':7, observs:2, ' ':6, CHISQRD:6:0);
                        WRITELN;
                        CLOSE(Datafile);
                        CLOSE(Outfile);}
              END ELSE IF PARAM=3 THEN
                  BEGIN
                        InitializeAssign;
                        RkBugGrwth20 := RkBugGrwth20 -
0.01;
                        DoIt;
                        SSR_BOD := SSR_BOD/observs;
                        WRITELN(' ':5, 'Rk Bug Grwth', '
':9, RkBugGrwth20:8:6, ' ':10, SSR_BOD:6:0, ' ':7,
observs:2, ' ':6, CHISQRD:6:0);
                        CLOSE(Datafile);
                        CLOSE(Outfile);
                        InitializeAssign;
                        RkBugGrwth20 := RkBugGrwth20 +
0.01;
                        DoIt;
                        SSR_BOD := SSR_BOD/observs;
                        WRITELN(' ':26, RkBugGrwth20:8:6, '
':10, SSR_BOD:6:0, ' ':7, observs:2, ' ':6, CHISQRD:6:0);
                        WRITELN;
                        CLOSE(Datafile);
                        CLOSE(Outfile);
               END ELSE IF PARAM=4 THEN
                   BEGIN
                        InitializeAssign;
                        RtBugGrwth20 := RtBugGrwth20 - 0.1;
                        DoIt;
                        SSR_BOD := SSR_BOD/observs;
                        WRITELN(' ':5, 'Rt Bug Grwth', '
':9, RtBugGrwth20:7:5, ' ':11, SSR_BOD:6:0, ' ':7,
observs:2, ' ':6, CHISQRD:6:0);
                        CLOSE(Datafile);
                        CLOSE(Outfile);
                        InitializeAssign;
                        RtBugGrwth20 := RtBugGrwth20 + 0.1;
                        DoIt;
                        SSR_BOD := SSR_BOD/observs;
                        WRITELN(' ':26, RtBugGrwth20:7:5, '
':11, SSR_BOD:6:0, ' ':7, observs:2, ' ':6, CHISQRD:6:0);
                        WRITELN;
                        CLOSE(Datafile);
                        CLOSE(Outfile);
               END ELSE IF PARAM=5 THEN
                   BEGIN
                        InitializeAssign;
                        C_settle_frac   := C_settle_frac -
0.2;
                        DoIt;
```

```
                        SSR_BOD := SSR_BOD/observs;
                        WRITELN(' ':5, 'C_settle_frac', '
':8, C_settle_frac:6:4, ' ':12, SSR_BOD:6:0, ' ':7,
observs:2, ' ':6, CHISQRD:6:0);
                        CLOSE(Datafile);
                        CLOSE(Outfile);
                        InitializeAssign;
                        C_settle_frac   := C_settle_frac +
0.2;
                        DoIt;
                        SSR_BOD := SSR_BOD/observs;
                        WRITELN(' ':26, C_settle_frac:6:4,
' ':12,SSR_BOD:6:0, ' ':7, observs:2, ' ':6, CHISQRD:6:0);
                        CLOSE(Datafile);
                        CLOSE(Outfile);
              END ELSE IF PARAM=6 THEN
                  BEGIN
{                        InitializeAssign;
                        dead_rt_mass := dead_rt_mass -
1000;
                        HoldDRM := dead_rt_mass;
                        DoIt;
                        SSR_BOD := SSR_BOD/observs;
                        WRITELN;
                        WRITELN(' ':5, 'Dead Rt Mass', '
':9, HoldDRM:5:1, ' ':12, SSR_BOD:6:0, ' ':7, observs:2, '
':6, CHISQRD:6:0);
                        CLOSE(Datafile);
                        CLOSE(Outfile);
                        InitializeAssign;
                        dead_rt_mass := dead_rt_mass +
1000;
                        HoldDRM := dead_rt_mass;
                        DoIt;
                        SSR_BOD := SSR_BOD/observs;
                        WRITELN(' ':26, HoldDRM:5:1,
' ':12, SSR_BOD:6:0, ' ':7, observs:2, ' ':6,
CHISQRD:6:0);
                        CLOSE(Datafile);
                        CLOSE(Outfile);}
              END ELSE IF PARAM = 7 THEN
                  BEGIN
                        InitializeAssign;
                        C_sys_mass := C_sys_mass - 1000;
                        CSM_hold   := C_sys_mass;
                        DoIt;
                        SSR_BOD := SSR_BOD/observs;
                        WRITELN;
                        WRITELN(' ':5, 'Init''l C conc ', '
':7, CSM_hold:3:1, ' ':12, SSR_BOD:6:0, ' ':7, observs:2,
' ':6, CHISQRD:6:0);
                        CLOSE(Datafile);
```

```
                        CLOSE(Outfile);
                        InitializeAssign;
                        C_sys_mass := C_sys_mass + 1000;
                        CSM_hold   := C_sys_mass;
                        DoIt;
                        SSR_BOD := SSR_BOD/observs;
                        WRITELN(' ':26, CSM_hold:3:1, '
':12, SSR_BOD:6:0, ' ':7, observs:2, ' ':6, CHISQRD:6:0);
                        CLOSE(Datafile);
                        CLOSE(Outfile);
              END ELSE IF PARAM=8 THEN
                  BEGIN
{                        InitializeAssign;
                     rt_area_to_vol := rt_area_to_vol - 5;
                        DoIt;
                        SSR_BOD := SSR_BOD/observs;
                        WRITELN;
                        WRITELN(' ':5, 'rt area to vol', '
':11, rt_area_to_vol:2:0, ' ':12, SSR_BOD:6:0, ' ':7,
observs:2, ' ':6, CHISQRD:6:0);
                        CLOSE(Datafile);
                        CLOSE(Outfile);
                        InitializeAssign;
                    rt_area_to_vol := rt_area_to_vol + 5;
                        DoIt;
                        SSR_BOD := SSR_BOD/observs;
                        WRITELN(' ':30, rt_area_to_vol:2:0,
' ':12,SSR_BOD:6:0, ' ':7, observs:2, ' ':6, CHISQRD:6:0);
                        CLOSE(Datafile);
                        CLOSE(Outfile);}
             END ELSE IF PARAM=9 THEN
                 BEGIN
                        DoIt;
                        SSR_BOD := SSR_BOD/observs;
                        WRITELN(' ':5, 'avg_rck_size', '
':8, avg_rck_size:5:3, ' ':11, SSR_BOD:6:0, ' ':7,
observs:2, ' ':6, CHISQRD:6:0);
                        CLOSE(Datafile);
                        InitializeAssign;
                    avg_rck_size := avg_rck_size  - 0.1;
                        DoIt;
                        SSR_BOD := SSR_BOD/observs;
                        WRITELN(' ':26, avg_rck_size:5:3, '
':11,SSR_BOD:6:0, ' ':7, observs:2, ' ':6, CHISQRD:6:0);
                        CLOSE(Datafile);
                        InitializeAssign;
                        avg_rck_size := avg_rck_size + 0.1;
                        DoIt;
                        SSR_BOD := SSR_BOD/observs;
                        WRITELN(' ':26, avg_rck_size:5:3, '
':11,SSR_BOD:6:0, ' ':7, observs:2, ' ':6, CHISQRD:6:0);
                        WRITELN;
```

```
                        CLOSE(Datafile);
                        CLOSE(Outfile);
              END ELSE IF PARAM=10 THEN
                  BEGIN
                        InitializeAssign;
                        init_por := init_por - 0.2;
                        DoIt;
                        SSR_BOD := SSR_BOD/observs;
                        WRITELN(' ':5, 'init_porosity', '
':11, init_por:5:3, ' ':12, SSR_BOD:6:0, ' ':7, observs:2,
' ':6, CHISQRD:6:0);
                        CLOSE(Datafile);
                        InitializeAssign;
                        init_por := init_por + 0.2;
                        DoIt;
                        SSR_BOD := SSR_BOD/observs;
                        WRITELN(' ':26, init_por:5:3, '
':12, SSR_BOD:6:0, ' ':7, observs:2, ' ':6, CHISQRD:6:0);
                        WRITELN;
                        CLOSE(Datafile);
                        CLOSE(Outfile);
                  END;
     END;
END;           {Subroutine GradientSearch}


BEGIN {Main Program!}
     Initialize;
     ASC     := FALSE;
     BETWEEN := FALSE;
     AssignPhyslParameters;
     AssignPlantParameters;
     HoldDRM := dead_rt_mass;
     AssignCarbonParameters;
     DoIt;
     SSRobs := SSR_BOD/observs;
     CLRSCR;
     WRITELN(Outfile);
     WRITELN(Outfile, ' ':20, 'SSR BOD was ', SSR_BOD:6:0,
                ' , SSR BOD per obs was ', SSRobs:3:0);
     WRITELN(Outfile, ' ':20, 'CHI SQRD was ',
CHISQRD:6:0, ' and final mass of carbon was ',
C_sys_mass:5:0);
     WRITELN(' ':20, 'SSR BOD was ', SSR_BOD:6:0,
             ' , SSR BOD per obs was ', SSRobs:3:0);
     WRITELN(' ':20, 'CHI SQRD was ', CHISQRD:6:0,
          ' and final mass of carbon was ',
C_sys_mass:5:0);
     WRITELN(' ':20, 'live sht mass = ',
live_sht_mass:4:0, ' , dead sht mass = ',
dead_sht_mass:4:0);
     WRITELN(' ':20, ' , live rt mass  = ',
```

```
live_rt_mass:4:0, ' , dead rt mass = ', dead_rt_mass:4:0);
     CLOSE(Datafile);
     CLOSE(Outfile);
     GradientSearch;
END.
```

COMPUTER MODEL FOR FULL-SCALE SYSTEM

```
{This program uses a datafile containing daily climatic (air
and water temperature, precipitation, evaporation, and solar
declination), influent flow data, and BOD5 analyses and
predicts the effluent BOD5 concentration using a finite
section approach. }


CONST
     PI       = 3.1415927;
     Limit    = 11;            {months}
     sects    = 2;

VAR
   month1, month2, air_tmp_oF_1, air_tmp_oF_2,
  wt_tmp_oF_1, wt_tmp_oF_2, BOD_in1, BOD_in2, BOD_out1,
   BOD_out2, Run, section, mid_sect, observs
                                         :INTEGER;

   titleline
                                                    :STRING[80];


  month, mo, HMonth, rck_dpth, init_por, length, width,
  sys_wat_vol, outlet_dpth, surf_area, avg_rck_size,
  rck_surf_area, lat, HQ_in, H_air_tmp_oF, Hdecl, decl1,
  decl2, Hppn, wat_dpth, inlet_dpth, D_S_L, D_S_M, D_R_M,
  L_R_M, L_S_M, Q_in1, Q_in2, meas_Q_out1, meas_Q_out2,
  live_sht_mass,  dead_sht_mass,  mid_BOD1,  mid_BOD2,
  rt_to_sht, live_rt_mass, dead_rt_mass, litterfall_rate,
  percent_harvest,   sht_decay_rate,   dy_SpgEqunx2,
  air_tmp_oC_1, air_tmp_oC_2, H_air_tmp_oC, sol_hlf_dy1,
  sol_hlf_dy2,  H_sol_hlf_dy,  net_prodn,  tot_rt_mass,
  dead_shts_lft, C_in1, C_in2, C_out1, C_out2, Q_in, ppn,
  air_tmp_oF,  air_tmp_oC,  decl,  wt_tmp_oC,  C_in,
  sol_hlf_dy,  H_wt_tmp_oC,  HC_in,  C_per_plant,
  C_assln_rate_20,  C_assln_rate,  C_assld,  C_out,
  plt_decay_C,  calc_C_out,  calc_BOD_out,  calc_mid_BOD,
  rck_bug_mass,  rt_bug_mass,  rt_surf_area,  rt_dnsty,
  RkBugGrwth20,  RkBugGrwth,  RtBugGrwth20,  RtBugGrwth,
  meas_Q_out, C_sttld, C_settle_frac, HmeasQ_out, SR_BOD,
  SSR_BOD, rt_area_to_vol, alpha, lambda, nu, psi, ro,
  CHISQ, CHISQRD, wt_tmp_oC_1, wt_tmp_oC_2, ppn1, ppn2,
  ET1,  ET2,  ET,  HET,  num_rcks,  C_into,  dt,  time,
  init_C_conc, SSRobs                      : REAL;


  litterfall, NP, DSL, DSM, DRM, LRM, LSM
                                       : ARRAY[1..4] OF REAL;

  Q_out, C_sx_mass, C_sx        : ARRAY[1..sects] OF REAL;
```

```
   dC                        : ARRAY[1..4, 1..sects] OF REAL;

   Datafile, Outfile                      : TEXT;


PROCEDURE Initialize;
BEGIN
     ASSIGN(Datafile, 'rslt\DS89.pas');
     RESET(Datafile);
     ASSIGN(Outfile, 'rslt\dsout.pas');
     REWRITE(Outfile);
     READLN(Datafile);
     READLN(Datafile);
     READLN(Datafile);
     READLN(Datafile);
     READLN(Datafile);
     WRITELN(Outfile, ' ':22, 'DENHAM SPRINGS ROCK-PLANT
FILTER');
     WRITELN(Outfile,  '  ':22,  '        BOD  MODEL
CALCULATIONS');
     WRITELN(Outfile);
     WRITELN(Outfile, ' ':10, '  Month      meas''d
calc''d      meas''d',
                        '       calc''d');
     WRITELN(Outfile, ' ':10, '           mid BOD     mid
BOD     end BOD',
                        '     end BOD');
        W R I T E L N ( O u t f i l e ,   '    ' : 1 0 ,   '
__________________________________________',
                        '____________');
     WRITELN(Outfile);
{     WRITELN(' ':10, 'sx    C in      plts      assld
sttld      C out');}
END;

PROCEDURE AssignPhyslParameters;
BEGIN
     observs       := 0;
     month         := 0;
     rck_dpth      := 2;                    {ft}
     init_por      := 0.4;
     length        := 1000;                 {ft}
     width         := 220;                  {ft}
     wat_dpth      := 1.85;
     sys_wat_vol   := wat_dpth * length * width * init_por;
    {cu ft}
     inlet_dpth    := 2.15;                 {ft}
     outlet_dpth   := 1.66;                  {ft}
     surf_area     := length * width;         {sq ft}
     avg_rck_size := SQRT(1 * 3)/12;         {ft}
     num_rcks            :=  (1-init_por)  *  rck_dpth  *
surf_area/sects/(PI *
```

```
                    (EXP(3 * LN(avg_rck_size)))/6);
     rck_surf_area:= num_rcks * PI * SQR(avg_rck_size);
{sq ft}
     rck_bug_mass := rck_surf_area * SQR(30.48) * EXP(-4 *
LN(10)); {mg}
     lat          := (29+56/60+53/3600) * PI/180;
     time         := 0;
END;


PROCEDURE AssignPlantParameters;
BEGIN
     live_sht_mass   := 40000.0;            {gms}
     dead_sht_mass   := 0;
     rt_to_sht       := 1; {1; from Kadlec & Hammer, 1988}
     live_rt_mass    := live_sht_mass * rt_to_sht;
     dead_rt_mass    := 400;                  {gms}
     litterfall_rate := 0.2; {0.2/day; K & H, 1988 * 10}
     percent_harvest := 0;
     sht_decay_rate  := 0.004;   {0.004/day; K & H, 1988 *
10}
     rt_death_rate   := 0.00001;
     rt_decay_rate   := 0.004;   {0.004 1/day; K & H, 1988
* 10}
     dead_shts_lft   := 0;
     rt_dnsty        := 0.7;
     rt_area_to_vol   := 8; {80; based on 0.05 cm diam
cylindrical root; sq area/vol}
     alpha          := -0.00034; {-0.00034 m^2/g; Morris,
1984}
     lambda          := 33;  {33 mW/cm^2; Morris, 1984}
     nu              := 0.36; {0.36% dry wt; Morris, 1984}
     psi             := 0.00071;   {0.00071/oC/hr; Morris,
1984}
     ro             := 0.000023; {0.000023/oC/hr; Morris,
1984}
END;


PROCEDURE AssignCarbonParameters;
BEGIN
     C_per_plant          := 429;        {429 mg/g; Morris,
Houghton, and Botkin, 1984, Ecol'l Modelling, v26,
pp155-175}
     RkBugGrwth20      := 1.0E-7;
     RtBugGrwth20      := 0.1;
     C_settle_frac     := 0.5;
     SSR_BOD           := 0;
     CHISQRD           := 0;
     init_C_conc       := 15;
     FOR section := 1 to sects DO
          C_sx_mass[section] := init_C_conc * 28.315585 *
```

```
sys_wat_vol/sects;   {mg}
END;


PROCEDURE ReadData;
BEGIN
     IF month = 0 THEN
     BEGIN
          READLN(Datafile,  month1,  Q_in1,  meas_Q_out1,
air_tmp_oF_1, wt_tmp_oF_1, BOD_in1, mid_BOD1, BOD_out1,
ppn1, ET1, decl1, dy_SpgEqunx1);
          READLN(Datafile,  month2,  Q_in2,  meas_Q_out2,
air_tmp_oF_2, wt_tmp_oF_2, BOD_in2, mid_BOD2, BOD_out2,
ppn2, ET2, decl2, dy_SpgEqunx2);
          decl1            := decl1/180 * PI;
          decl2            := decl2/180 * PI;
          air_tmp_oC_1     := (air_tmp_oF_1 - 32)/9 * 5;
          air_tmp_oC_2     := (air_tmp_oF_2 - 32)/9 * 5;
          wt_tmp_oC_1     := (wt_tmp_oF_1 - 32)/9 * 5;
          wt_tmp_oC_2     := (wt_tmp_oF_2 - 32)/9 * 5;
          sol_hlf_dy1      := (122.142857 - dy_SpgEqunx1/3)
* PI/180;
          sol_hlf_dy2      := (122.142857 - dy_SpgEqunx2/3)
* PI/180;
          C_in1             := BOD_in1/0.65625; {Metcalf &
Eddy}
          C_in2            := BOD_in2/0.65625;
          C_out1               := BOD_out1/0.65625;
{Metcalf & Eddy}
          C_out2           := BOD_out2/0.65625;
          Q_in1            := Q_in1 * 1000000.0/7.481;
       {cfd}
          meas_Q_out1     := meas_Q_out1 * 1000000.0/7.481;
      {cfd}
          Q_in2            := Q_in2 * 1000000.0/7.481;
       {cfd}
          meas_Q_out2     := meas_Q_out2 * 1000000.0/7.481;
      {cfd}
          ppn1                     :=  ppn1/12  *  length  *
width/sects/30;  {cfd}
          ET1                       :=  ET1/12  *  length  *
width/sects/30;  {cfd}
          ppn2                     :=  ppn2/12  *  length  *
width/sects/30;  {cfd}
          ET2                       :=  ET2/12  *  length  *
width/sects/30;  {cfd}
          month            := month + 1;
     END ELSE
     BEGIN
        month1        :=  month2;
        Q_in1         :=  Q_in2;
        meas_Q_out1   :=  meas_Q_out2;
```

```
        air_tmp_oF_1 :=  air_tmp_oF_2;
        air_tmp_oC_1 :=  air_tmp_oC_2;
        wt_tmp_oC_1  :=  wt_tmp_oC_2;
        BOD_in1      :=  BOD_in2;
        mid_BOD1     :=  mid_BOD2;
        BOD_out1     :=  BOD_out2;
        decl1        :=  decl2;
        ppn1         :=  ppn2;
        ET1          :=  ET2;
        dy_SpgEqunx1 :=  dy_SpgEqunx2;
        sol_hlf_dy1  :=  sol_hlf_dy2;
        C_in1           := C_in2;
        C_out1          := C_out2;
        READLN(Datafile,   month2,   Q_in2,   meas_Q_out2,
air_tmp_oF_2, wt_tmp_oF_2, BOD_in2,  mid_BOD2, BOD_out2,
ppn2, ET2, decl2, dy_SpgEqunx2);
        decl2           := decl2/180 * PI;
        air_tmp_oC_2    := (air_tmp_oF_2 - 32)/9 * 5;
        wt_tmp_oC_2     := (wt_tmp_oF_2 - 32)/9 * 5;
        sol_hlf_dy2     := (122.142857 - dy_SpgEqunx2/3) *
PI/180;
        C_in2           := BOD_in2/0.65625;
        C_out2          := BOD_out2/0.65625;
        Q_in2           := Q_in2 * 1000000.0/7.481;
     {cfd}
        meas_Q_out2     := meas_Q_out2 * 1000000.0/7.481;
     {cfd}
        ppn2                      :=  ppn2/12  *  length  *
width/sects/30;  {cfd}
        ET2            := ET2/12 * length * width/sects/30;
 {cfd}
        month           := month + 1;
        END;
END;


FUNCTION sol_radn_mWcc(time, decl, sol_hlf_dy: REAL): REAL;

VAR
   rad_decl, sol_dist_ratio, N
        :REAL;

BEGIN
     rad_decl:= decl/180 * PI;
     sol_dist_ratio := 0.9942632+(0.000316 * time);
     sol_radn_mWcc     :=   0.56   *   1440/PI   *   139.5   *
sol_dist_ratio *
                            ((PI/2    *    SIN(lat)    *
SIN(rad_decl))+(COS(lat) *
                       COS(rad_decl) * SIN(sol_hlf_dy)));
     N                      := 0.56  * 1440/PI  * 139.5  *
sol_dist_ratio *
```

```
                              ((PI/2    *    SIN(lat)    *
SIN(rad_decl))+(COS(lat) *
                          COS(rad_decl) * SIN(sol_hlf_dy)));
END;


FUNCTION SunAngle(decl: REAL) :REAL;
{This function involves finding the arc cosine, in radians,
of "B", as
directed on pgs 8 & 9 of "Pascal Programs for Scientists and
Engineers"}

VAR
   A, B, C, M
         :REAL;

BEGIN
     B := -SIN(decl)/COS(lat);
     IF B=0.0 THEN SunAngle := PI/2
     ELSE
         IF B=1.0 THEN SunAngle := 0.0
         ELSE
             IF B=-1.0 THEN SunAngle := PI
             ELSE
                 BEGIN
                      C := B/SQRT(1.0 - SQR(B));
                      A := ARCTAN(ABS(1/C));
                      IF C>0.0 THEN
                         BEGIN
                              SunAngle := A;
                         END
                      ELSE
                          BEGIN
                               SunAngle := PI - A;
                               M        := PI - A;
                          END;
                 END;
END;


PROCEDURE PlantRunges;

VAR
   gp, resp
          :REAL;

BEGIN
     IF air_tmp_oC <= 0 THEN
     BEGIN
          ro  := 0;
          psi := 0;
     END ELSE
```

```
     BEGIN
          ro  := 0.000023;
          psi := 0.00071;
     END;
     gp                      := psi * air_tmp_oC * 4 *
SIN(SunAngle(decl))   *   (LN(sol_radn_mWcc(mo,   decl,
sol_hlf_dy)  *  EXP(alpha  *  live_sht_mass/(surf_area  *
SQR(0.3048)))/ SIN(SunAngle(decl))) + lambda) -
LN(sol_radn_mWcc(mo, decl, sol_hlf_dy) + lambda))/ (alpha *
(4 + nu)) * 24 * SQR(0.3048)*surf_area;      {g/day}
     resp          := (ro * air_tmp_oC*(1+rt_to_sht) *
(live_sht_mass/(surf_area*SQR(0.3048)))) * 24 * SQR(0.3048)
* surf_area;      {g/day}
     NP[Run]          := gp - resp;
     IF (live_sht_mass > 0) THEN
        DSL[Run]      := ((litterfall_rate * live_sht_mass)
- (percent_harvest/100/dt * dead_sht_mass)) * dt  {gms}
     ELSE DSL[Run]    := 0;
     DSM[Run]          := dead_shts_lft - (sht_decay_rate *
dead_shts_lft * dt); {gms}
     IF live_rt_mass > 0 THEN
        DRM[Run]      := (rt_death_rate * live_rt_mass -
             rt_decay_rate * dead_rt_mass) * dt {gms}
     ELSE DRM[Run]    := 0;
     LRM[Run]        := ((rt_to_sht/(1+rt_to_sht)) * NP[Run]
- live_rt_mass *  rt_death_rate) * dt;   {gms}
     rt_surf_area              :=    LRM[Run]/rt_dnsty    *
rt_area_to_vol/sects; {sq cm}
     rt_bug_mass        := EXP(5 * LN(10)) * rt_surf_area *
EXP(-9 * LN(10)); {mg} {a hundred thous bugs/ sq cm - Dr
Ralph; one billionth mg per bug - Handbook}
     LSM[Run]            := ((1/(1+rt_to_sht)) * NP[Run] -
litterfall_rate * live_sht_mass) * dt;   {gms}
     litterfall[Run] := litterfall_rate * live_sht_mass;
{gms/day}
END;


PROCEDURE SectionCarbonMass;
BEGIN
     Q_out[1] := Q_in + ppn - ET;     {cfd}
     FOR section := 2 to sects DO
         Q_out[section] := Q_out[section - 1] + ppn - ET;
     RkBugGrwth  := RkBugGrwth20 * EXP((wt_tmp_oC - 20) *
LN(1.047));
     RtBugGrwth  := RtBugGrwth20 * EXP((wt_tmp_oC - 20) *
LN(1.047));
     plt_decay_C  :=  (C_per_plant  *  (sht_decay_rate  *
dead_sht_mass + rt_decay_rate * dead_rt_mass))/sects * dt;
 {mg}
{     WRITELN;}
     FOR section := 1 to sects DO
```

```
     BEGIN
          IF section = 1 THEN
               C_into := C_in * Q_in * 28.315585 * dt
          ELSE  C_into   :=   C_sx_mass[section   -   1]   *
Q_out[section - 1]/ sys_wat_vol/sects * dt;
          IF C_sx_mass[section] > 0 THEN
          BEGIN
               C_assld := C_sx_mass[section] * (RkBugGrwth
* rck_bug_mass + RtBugGrwth * rt_bug_mass) * dt;
                  C_sttld    :=    C_settle_frac    *
C_sx_mass[section];
               C_out   := C_sx_mass[section] *
                    Q_out[section]/sys_wat_vol/sects * dt;
          END ELSE
          BEGIN
               C_assld := 0;
               C_sttld := 0;
               C_out   := 0;
          END;
          dC[Run, section] := C_into + plt_decay_C - C_assld
- C_sttld - C_out;
     END;
END;   {PROCEDURE SectionCarbonMass}


PROCEDURE Rungematic;
BEGIN
     HMonth        := (month1 + month2)/2;
     HQ_in         := (Q_in1 + Q_in2)/2;
     HmeasQ_out    := (meas_Q_out1 + meas_Q_out2)/2;
     Hppn          := (ppn1 + ppn2)/2;
     HET           := (ET1 + ET2)/2;
     H_air_tmp_oF := (air_tmp_oF_1 + air_tmp_oF_2)/2;
     H_air_tmp_oC := (air_tmp_oC_1 + air_tmp_oC_2)/2;
     H_wt_tmp_oC  := (wt_tmp_oC_1 + wt_tmp_oC_2)/2;
     H_sol_hlf_dy := (sol_hlf_dy1 + sol_hlf_dy2)/2;
     Hdecl         := (decl1 + decl2)/2;
     HC_in         := (C_in1 + C_in2)/2;
     REPEAT
           Run           := 1;
           L_S_M         := live_sht_mass;
           D_S_L         := dead_shts_lft;
           D_S_M         := dead_sht_mass;
           D_R_M         := dead_rt_mass;
           L_R_M         := live_rt_mass;
           FOR section := 1 to sects DO
               C_sx[section] := C_sx_mass[section];
           FOR Run:=1 TO 4 DO
           BEGIN
                IF Run=1 THEN
                BEGIN
                     mo           := month1;
```

```
                        Q_in          := Q_in1;
                        meas_Q_out    := meas_Q_out1;
                        air_tmp_oC    := air_tmp_oC_1;
                        air_tmp_oF    := air_tmp_oF_1;
                        wt_tmp_oC     := wt_tmp_oC_1;
                        C_in          := C_in1;
                        ppn           := ppn1;
                        ET            := ET1;
                        decl          := decl1;
                        sol_hlf_dy    := sol_hlf_dy1;
                        PlantRunges;
                        live_sht_mass:=    live_sht_mass    +
LSM[Run]/2;
                        dead_shts_lft:=    dead_shts_lft    +
DSL[Run]/2;
                        dead_sht_mass:=    dead_sht_mass    +
DSM[Run]/2;
                        dead_rt_mass   :=  dead_rt_mass     +
DRM[Run]/2;
                        live_rt_mass   :=  live_rt_mass     +
LSM[Run]/2;
                        SectionCarbonMass;
                        FOR section := 1 to sects DO
                                C_sx_mass[section]      :=
C_sx_mass[section] + dC[Run, section]/2;
                   END ELSE IF Run=2 THEN
                   BEGIN
                        mo            := Hmonth;
                        Q_in          := HQ_in;
                        meas_Q_out    := HmeasQ_out;
                        air_tmp_oC    := H_air_tmp_oC;
                        air_tmp_oF    := H_air_tmp_oF;
                        wt_tmp_oC     := H_wt_tmp_oC;
                        C_in          := HC_in;
                        ppn           := Hppn;
                        ET            := HET;
                        decl          := Hdecl;
                        sol_hlf_dy    := H_sol_hlf_dy;
                        PlantRunges;
                        live_sht_mass:=    live_sht_mass    +
LSM[Run]/2;
                        dead_shts_lft:=    dead_shts_lft    +
DSL[Run]/2;
                        dead_sht_mass:=    dead_sht_mass    +
DSM[Run]/2;
                        dead_rt_mass   :=  dead_rt_mass     +
DRM[Run]/2;
                        live_rt_mass   :=  live_rt_mass     +
LSM[Run]/2;
                        SectionCarbonMass;
                        FOR section := 1 to sects DO
                             C_sx_mass[section]      :=
```

```
C_sx_mass[section] + dC[Run, section]/2;
                END ELSE IF Run=3 THEN
                BEGIN
                     mo              := Hmonth;
                     Q_in           := HQ_in;
                     meas_Q_out     := HmeasQ_out;
                     air_tmp_oC     := H_air_tmp_oC;
                     air_tmp_oF     := H_air_tmp_oF;
                     wt_tmp_oC      := H_wt_tmp_oC;
                     C_in           := HC_in;
                     ppn            := Hppn;
                     ET             := HET;
                     decl           := Hdecl;
                     sol_hlf_dy     := H_sol_hlf_dy;
                     PlantRunges;
                     live_sht_mass:=    live_sht_mass    +
LSM[Run];
                     dead_shts_lft:=    dead_shts_lft    +
DSL[Run];
                     dead_sht_mass:=    dead_sht_mass    +
DSM[Run];
                     dead_rt_mass   :=  dead_rt_mass     +
DRM[Run];
                     live_rt_mass   :=  live_rt_mass     +
LSM[Run];
                     SectionCarbonMass;
                     FOR section := 1 to sects DO
                            C_sx_mass[section]    :=
C_sx_mass[section] + dC[Run, section];
                END ELSE IF Run=4 THEN
                BEGIN
                     mo             := month2;
                     Q_in           := Q_in2;
                     meas_Q_out     := meas_Q_out2;
                     air_tmp_oC     := air_tmp_oC_2;
                     air_tmp_oF     := air_tmp_oF_2;
                     wt_tmp_oC      := wt_tmp_oC_2;
                     C_in           := C_in2;
                     ppn            := ppn2;
                     ET             := ET2;
                     decl           := decl2;
                     sol_hlf_dy     := sol_hlf_dy2;
                     PlantRunges;
                     SectionCarbonMass;
                END;
           END;
           net_prodn     := (NP[1] + 2 * NP[2] + 2 *  NP[3]
+ NP[4])/6;
           live_sht_mass:= L_S_M + (LSM[1] + 2 * LSM[2] +
                           2 *  LSM[3] + LSM[4])/6;
           dead_shts_lft:= D_S_L + (DSL[1] + 2 * DSL[2] +
                           2 *  DSL[3] + DSL[4])/6;
```

```
            dead_sht_mass:= D_S_M + (DSM[1] + 2 * DSM[2] +
                             2 *  DSM[3] + DSM[4])/6;
            dead_rt_mass := D_R_M + (DRM[1] + 2 * DRM[2] +
                             2 *  DRM[3] + DRM[4])/6;
            live_rt_mass := L_R_M + (LRM[1] + 2 * LRM[2] +
                             2 *  LRM[3] + LRM[4])/6;
            tot_rt_mass  := dead_rt_mass + live_rt_mass;
    {gms}
            FOR section := 1 to sects DO
                 C_sx_mass[section]   :=   C_sx[section]   +
(dC[1,section] + 2 * dC[2, section] + 2 * dC[3, section] +
dC[4, section])/6;
            time := time + dt;
     UNTIL time > 30;
     calc_BOD_out := C_sx_mass[sects]/ (sys_wat_vol/sects *
28.315585) * 0.65625;
     mid_sect      := TRUNC(sects/2);
     calc_mid_BOD:=C_sx_mass[mid_sect]/(sys_wat_vol/sects
* 28.315585) *  0.65625;
     IF mid_BOD1 <>0 THEN
     BEGIN
        WRITELN(Outfile,   '   ':12,   month2:2,   '   ':8,
mid_BOD1:4:0, ' ':8, calc_mid_BOD:4:0, ' ':8, BOD_out1:4, '
':8, calc_BOD_out:4:0);
     END ELSE BEGIN
        WRITELN(Outfile,   '   ':12,   month2:2,   '   ':32,
BOD_out1:4, ' ':8, calc_BOD_out:4:0);
     END;
     observs   := observs + 1;
     SR_BOD    := SQR(BOD_out1 - calc_BOD_out);
     SSR_BOD   := SSR_BOD + SR_BOD;
     CHISQ    := SQR(BOD_out1 - calc_BOD_out)/calc_BOD_out;
     CHISQRD   := CHISQRD + CHISQ;
END;


PROCEDURE InitializeAssign;
BEGIN
     Initialize;
     AssignPhyslParameters;
     AssignPlantParameters;
     AssignCarbonParameters;
END;



PROCEDURE DoIt;
BEGIN
     WHILE month < Limit DO
     BEGIN
```

```
          ReadData;
          Rungematic;
     END;
END;


BEGIN {Main Program!}
     Initialize;
     AssignPhyslParameters;
     AssignPlantParameters;
     AssignCarbonParameters;
     ReadData;
     dt := sys_wat_vol/sects/Q_in1;     {days}
     Rungematic;
     DoIt;
     SSRobs := SSR_BOD/observs;
     CLRSCR;
     WRITELN(Outfile);
     WRITELN(Outfile, ' ':20, 'SSR BOD was ', SSR_BOD:6:0,
                      '  ,  SSR  BOD  per  obs  was  ',
SSRobs:3:0);
     WRITELN(Outfile, ' ':20, 'CHI SQRD was ', CHISQRD:6:0);

     CLOSE(Datafile);
     CLOSE(Outfile);
END.
```

TABLE B.1
DENHAM SPRINGS ROCK-PLANT FILTER DATA
East Cell

Mo	Qin (MGD)	Qout (MGD)	air oF	wat oF*	BOD in (mg/l)	mid BOD (mg/l)	BOD out (mg/l)	ppn (in/mo)	evap. (in/mo)
12	0.805	0.565	53	55	38	28	11	6.63	2.5
1	1.058	0.748	59	59	38	36	20	4.02	2.62
2	0.572		54	55	41	34	22	1.51	2.81
3	0.572		63	63	34		8	4.64	4.62
4	0.278		67	70	31		16	2.34	6.13
5	0.494	0.605	77	78	42		16	14.67	6.98
6	0.532	0.677	80	82	35	26	10	23.18	6.58
7	0.671	0.803	82	84	26	7	5	6.25	6.56
8	0.418	0.464	83	84	18	8	6	5.16	6.73
9	0.732	0.375	77	81	21	9	6	4.51	6.02
10	0.409	0.38	68	71	25	16	6	2.18	4.95
11	0.687	0.466	61	63	26	14	9	13.55	3.21

* Estimated from soil temperatures listed in local climatological data.

APPENDIX C

Listing of Simulation Results

TABLE C.1
DENHAM SPRINGS ROCK-PLANT FILTER
FLOW MODEL CALCULATIONS
(Flow values in cfd)

Month	meas'd flow	calc'd flow
1	99987	142280
2	0	75666
3	0	76473
4	0	34845
5	80872	70733
6	90496	81258
7	107339	89504
8	62024	54915
9	50127	96925
10	50795	52979
11	62291	98152

TABLE C.2
Live Shoot Mass
Sagittaria Systems
(LSM values in grams)

Day	LSM calc'd	LSM meas'd
2	485	
3	497	
4	509	1412
5	521	
6	530	
7	543	
8	559	
9	575	
10	594	
11	612	714
12	627	
13	645	
14	664	
15	683	
16	705	
17	724	
18	740	
19	759	
20	779	
21	792	702
22	793	
23	789	
24	789	
25	793	
26	798	
27	801	
28	807	
29	815	
30	819	
31	809	549
32	786	
33	767	
34	752	
35	735	
36	719	
37	707	
38	695	
39	685	
40	682	
41	678	556
42	671	
43	665	
44	657	
45	647	

46	637	
47	628	
48	621	
49	617	
50	613	
51	605	
52	604	
53	608	
54	601	
55	582	
56	565	
57	558	
58	553	
59	542	
60	538	
61	535	579
62	529	
63	521	
64	514	
65	506	
66	500	
67	493	
68	485	
69	475	
70	466	
71	457	
72	447	
73	445	
74	443	
75	437	
76	430	
77	422	
78	415	
79	411	
80	406	

TABLE C.3
Live Shoot Mass
Scirpus System
(LSM values in grams)

Day	LSM calc'd	LSM meas'd
2	3065	
3	3139	
4	3214	
5	3283	3155
6	3341	
7	3421	
8	3524	
9	3623	
10	3739	
11	3852	3026
12	3943	
13	4053	
14	4174	
15	4291	
16	4428	
17	4542	
18	4639	
19	4758	
20	4880	
21	4954	3955
22	4958	
23	4933	
24	4927	
25	4952	
26	4976	
27	4991	
28	5026	
29	5071	
30	5096	
31	5029	
32	4886	5314
33	4765	
34	4666	
35	4561	
36	4457	
37	4382	
38	4309	
39	4245	
40	4224	
41	4195	
42	4150	4674
43	4113	
44	4060	

45	4000	
46	3933	
47	3875	
48	3833	
49	3807	
50	3781	
51	3733	
52	3722	
53	3749	
54	3701	
55	3582	
56	3481	
57	3437	
58	3400	
59	3337	
60	3308	
61	3292	4271
62	3250	
63	3202	
64	3156	
65	3109	
66	3070	
67	3025	
68	2975	
69	2914	
70	2860	
71	2801	
72	2744	
73	2726	
74	2713	
75	2679	
76	2634	
77	2586	
78	2543	
79	2516	
80	2484	

TABLE C.4
SAGITTARIA System Effluent BOD5
(BOD5 values in mg/l)

		calc'd BOD5 out:		
Day	meas'd BOD5 out	Computer Model	EPA Model*	European Model
2	29.3	18.8	7.9	9.5
4	17.0	16.5	6.7	8.1
6	6.7	14.7	4.4	6.3
8	8.5	14.8	5.8	8.2
9	11.5	14.5	5.5	7.7
10	10.7	15.4	6.8	8.9
12	17.8	27.2	21.1	25.2
14	36.7	26.7	14.7	17.7
16	45.2	30.3	19.2	25.1
18	37.4	31.2	21.1	25.2
19	37.4	33.1	24.0	26.8
20	45.6	34.7	22.6	29.5
22	43.7	39.7	33.4	30.3
24	42.6	42.2	34.3	33.2
26	44.4	40.4	29.2	28.4
28	48.9	42.1	34.1	33.1
29	51.5	41.3	31.0	30.1
30	61.5	44.4	41.8	35.8
32	42.2	28.5	13.8	11.9
34	26.7	25.0	16.2	13.9
36	25.2	23.8	17.9	14.5
38	27.8	24.9	18.5	16.8
39	32.2	25.6	15.5	16.1
40	23.0	24.5	10.9	12.2
42	35.2	37.6	43.4	42.7
44	46.3	40.7	43.6	42.8
46	12.2	45.7	52.5	48.0
48	38.9	39.6	37.2	35.3
49	29.3	41.9	40.5	39.8
50	32.2	37.0	32.0	30.3
52	23.3	24.4	12.9	13.1
54	20.4	23.3	17.6	16.2
56	12.6	23.3	20.9	17.9
58	17.4	22.5	20.4	18.1
59	16.7	22.5	17.2	15.7
60	15.2	18.8	12.5	11.4
62	29.3	41.9	51.2	46.8
64	37.4	59.7	74.1	67.8
66	40.7	61.4	66.1	60.4
68	50.0	68.8	70.2	61.9
69	50.7	59.4	58.3	51.7
70	30.4	64.6	66.8	59.1

72	32.6	43.2	33.5	28.8
74	34.4	35.5	25.7	25.3
76	26.7	32.4	26.7	25.3
78	27.0	39.1	42.5	36.6
79	25.6	34.3	27.6	25.2
80	26.7	39.1	39.6	36.2

* K_{20} for the EPA model = 0.54/day

TABLE C.5
SCIRPUS System Effluent BOD5
(BOD5 values in mg/l)

Day	meas'd BOD5 out	calc'd BOD5 out: Computer Model	EPA Model*	European Model
2	28.5	13.6	6.2	9.8
4	10.7	13.8	4.9	7.9
6	8.1	12.5	3.6	6.3
8	7.8	12.8	4.3	8.2
9	8.5	12.6	3.9	7.5
10	7.8	13.6	4.9	8.8
12	10.4	23.0	15.2	24.2
14	31.5	21.1	10.1	17.7
16	27.8	23.8	14.4	25.1
18	32.6	25.2	16.8	24.2
19	25.2	26.7	18.3	26.4
20	40.4	27.6	18.9	30.0
22	38.1	32.8	30.2	31.7
24	38.1	34.4	26.7	32.7
26	34.8	32.6	23.6	28.8
28	31.5	34.3	25.9	31.7
29	26.7	34.0	25.9	29.3
30	53.7	38.0	33.6	35.3
32	34.1	23.9	11.1	11.7
34	23.0	22.3	13.0	13.7
36	18.9	21.6	14.7	14.5
38	17.8	22.2	14.6	16.5
39	14.4	21.5	12.5	16.6
40	31.1	19.5	10.1	12.4
42	29.6	32.0	37.8	42.5
44	36.7	38.1	38.4	43.0
46	22.2	40.4	46.4	47.8
48	33.3	34.2	32.5	34.9
49	33.7	38.3	35.7	40.0
50	39.6	32.2	28.1	30.2
52	23.0	21.1	11.1	13.1
54	15.6	23.7	14.8	15.9
56	12.6	24.2	18.7	17.8
58	13.3	21.5	18.1	17.9
59	5.6	21.9	15.9	15.7
60	10.7	17.6	11.1	11.4
62	24.8	37.2	45.7	47.1
64	40.7	53.6	67.6	66.9
66	50.7	57.2	60.2	59.5
68	58.9	56.6	64.1	63.5
69	43.3	48.9	51.3	50.7
70	42.6	58.2	62.0	59.1

72	31.1	37.5	30.2	28.8
74	30.4	30.8	22.4	25.2
76	23.0	30.2	22.7	24.4
78	24.1	37.8	38.5	36.7
79	25.2	33.7	25.4	25.1

* K_{20} for the EPA model = 0.65/day

TABLE C.6
CONTROL System Effluent BOD5
(BOD5 values in mg/l)

Day	meas'd BOD5 out	calc'd BOD5 out: Computer Model	EPA Model*	European Model
2	44.4	44.7	9.2	10.2
4	25.9	23.9	7.7	8.0
6	14.4	15.2	4.8	6.3
8	14.1	13.2	7.1	8.4
9	13.3	12.3	6.3	7.5
10	14.4	12.8	7.6	9.2
12	26.3	28.1	22.0	24.5
14	48.1	30.0	16.4	18.2
16	50.4	35.6	23.3	25.8
18	48.1	36.4	25.7	24.9
19	41.9	37.2	25.5	26.4
20	59.6	41.0	28.5	29.5
22	49.6	47.5	41.9	32.2
24	51.1	51.6	38.8	33.2
26	48.5	48.5	33.6	28.8
28	47.4	50.9	37.6	32.2
29	45.9	51.0	36.7	29.7
30	54.8	53.0	43.7	35.3
32	42.2	32.7	15.1	11.5
34	27.0	26.4	18.1	13.9
36	26.3	24.3	20.1	14.7
38	31.1	24.6	21.1	17.0
39	30.7	25.7	18.0	16.3
40	40.0	24.3	13.0	12.6
42	36.3	42.6	46.9	42.9
44	40.7	47.1	46.7	42.6
46	17.4	53.8	55.9	48.0
48	41.1	47.1	41.1	35.3
49	37.0	48.5	43.8	40.0
50	36.3	44.2	34.2	30.3
52	21.9	26.9	13.8	13.1
54	17.0	23.9	18.6	15.9
56	9.6	23.4	22.1	17.9
58	25.9	22.5	21.8	18.2
59	12.2	21.4	18.3	15.7
60	16.3	18.3	13.3	11.4
62	34.4	49.0	56.2	46.8
64	45.2	71.9	81.4	67.8
66	45.6	75.0	69.7	59.5
68	46.7	77.9	75.3	62.5
69	40.0	72.5	61.5	51.2
70	30.0	76.4	73.3	59.4

72	34.8	50.3	35.2	28.5
74	30.4	39.3	27.5	25.2
76	25.2	37.5	29.2	25.0
78	32.2	46.4	44.9	36.4
79	40.0	41.7	30.0	24.9
80	25.6	45.3	43.4	36.2

* K_{20} for the EPA model = 0.48/day

TABLE C.7
DENHAM SPRINGS ROCK-PLANT FILTER
BOD5 MODEL CALCULATIONS
Using the Computer Model
(BOD5 values in mg/l)

Month	meas'd mid BOD5	calc'd mid BOD5	meas'd end BOD5	calc'd end BOD5
1	28	56	11	20
2	36	53	20	19
3	34	46	22	16
4			8	13
5			16	10
6			16	10
7	26	32	10	9
8	7	27	5	8
9	8	25	6	7
10	9	24	6	7
11	16	25	6	7

SSR BOD5 was 227, SSR BOD5 per obs was 21 for 12 observations.

TABLE C.8
DENHAM SPRINGS ROCK-PLANT FILTER
BOD5 MODEL CALCULATIONS
Using EPA Model
(BOD5 values in mg/l)

Month	meas'd BOD5 out	calc'd BOD5 out
12	11.0	23.1
1	20.0	24.7
2	22.0	20.4
3	8.0	13.7
4	16.0	3.0
5	16.0	7.6
6	10.0	5.8
7	5.0	5.7
8	6.0	1.6
9	6.0	5.9
10	6.0	4.8
11	9.0	12.2

SSR BOD5 was 494 , SSR BOD5 per obs was 41 (12 obs), and K20 was 0.50

TABLE C.9
DENHAM SPRINGS ROCK-PLANT FILTER
BOD5 MODEL CALCULATIONS
Using Kickuth's Model
(BOD5 values in mg/l)

Month	meas'd BOD5 out	calc'd BOD5 out
12	11.0	10.5
1	20.0	14.2
2	22.0	6.7
3	8.0	5.5
4	16.0	0.7
5	16.0	5.1
6	10.0	5.0
7	5.0	5.5
8	6.0	1.5
9	6.0	5.1
10	6.0	2.0
11	9.0	5.7

SSR BOD5 was 699 , SSR BOD5 per obs was 58 for 12 observations.

APPENDIX D

Derivation of Equation (10)

Equation (10) in Chapter 4 of Part Two was derived fromt the carbon mass balance, equation (9), of Chapter 3, Part Two:

d[C mass] = [C_{in} + C from plant decay - C assimilated by microorganisms - C removed by settling - C_{out}] * dt (9)

where terms in the parentheses to the right are in units of mg carbon/day. By multiplying both sides by 0.656, the quantities are converted to BOD_5 mass. Then the following substitutions can be made:

(1) From Figures 2.9 and 2.10, the maximum carbon from plant decay in the bench-scale study was approximately 5 grams/day. Converting to BOD_5 and surface area loading, this number becomes 4.7 g/day/m^2 BOD_5. This approximation into equation (9) will give the highest of carbon from plant decay, according to the bench-scale study.

(2) To approximate the least BOD_5 degradation on the root surfaces, according to the Figures 2.4 and 2.5, a live root mass of 500 grams is assumed. This value is converted to microorganisms mass per surface area (the multiplier for the reaction constant on the roots) by the procedure outlined in Appendix B and dividing by the bench-scale system surface area is 0.82 g/m^2.

(3) For rock sizes ranging from 1" to 3", the mass of

microorganisms per surface area is 599 mg/m^2. This becomes the multiplier for the degradation reaction constant, K.

Substituting these values into (9), gives:

$$dC/dt = C_oQ_o - CQ_e + 4.7E\text{-}3A -$$
$$(0.82E\text{-}3AK_{rt} + 599AK_{rk} + 0.5)0.656CV \qquad \text{(g/day)}$$

Rearranging, this equation becomes:

$$dC/dt = C_oQ_o + 4.71E\text{-}3A -$$
$$[Q_e + (0.54E\text{-}3AK_{rt} + 393AK_{rk} + 0.3)V]C \qquad \text{(g/day)}$$

Which is of the form:

$$dC/dt = X - YC$$

since X and Y are known for a given system. When integrated, this equation becomes:

$$C_e = X/Y(1 - e^{-Yt}) + C_oe^{-Yt}$$

where C_e = effluent BOD_5 concentration, mg/l

C_o = influent BOD_5 concentration, mg/l

t = retention time, days

= $(2V)/(Q_o + Q_e)$

X = $C_oQ_o + 4.7E\text{-}3A$

Y = $Q_e + (393AKV)$

V = volume of water in filter, liters

Q_o, Q_e = influent and effluent flow rate, liters/day

A = filter surface area, meters^2

K = $1E\text{-}7(1.047)^{T-20}$ /mg microbes/day

T = water temperature, °C

Note that for Y in the above calculation, the $0.54E\text{-}3AK_{rt}$ and 0.5 terms can be neglected relative to the term for degradation of the rock surfaces, $393AK_{rk}$. Q_e in these equations can be taken as the lowest annual effluent flow rate calculated from local climatological data.

VITA

In 1954, Donna was born into a family of two boys, Greg and Steve. From this point, there was a lot of moving around for the Skipper family since Ed, their Dad, was an Air Force pilot. June, their Mom, worked in her home as a mother.

After leaving home in 1972, Donna obtained two undergraduate degrees from the University of Alabama and started skydiving. In 1979, she began working as an engineer, mostly for consulting firms; however, since her goal is to help make this world a cleaner place to live, she enrolled in graduate school at Louisiana State University in 1984 to specialize in Civil/ Environmental Engineering.

In addition to these achievements, Donna is a private pilot, an accelerated freefall jumpmaster, and has participated in three world record, all women skydives. Yet another of these world record skydives is planned for this summer.

Currently, Donna lives in Denham Springs, Louisiana with her loveable dog, Max. After designing an Interstate rest area contructed wetland wastewater treatment system for the Louisiana Transportation Research Center next year, she will begin a career as a college professor at an, as yet, unknown location.

DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Donna Skipper

Major Field: Civil Engineering

Title of Dissertation: A Rock-Plant Filter Bench-Scale Study and Computer Model

Approved:

Marty Tittlebaum

Major Professor and Chairman

H Keen

Dean of the Graduate School

EXAMINING COMMITTEE:

Dipan Roy.

Darrell Oathman

Stephen D. Field

Donald Dean Adrian

John M. Tyler

Date of Examination:

November 2, 1990